An investigation into the relationships between strength, flexibility and anthropometric discrepancies, on lower limbs asymmetry in athletes

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Research Thesis

December 2015

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Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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List of Abbreviations

Abbreviations have been assigned only to terms that are frequently used in this document

Abbreviation	Full Definition
1LCMJ	One-legged countermovement jump
1LH	One-legged hop
1LTH	One-legged triple hop
CMJ	Two-legged countermovement jump
AAV	Absolute asymmetry value
Abs	Absolute
ACL	Anterior cruciate ligament
AKE	Active Knee Extension
ANOVA	Analysis of Variance
ASIS	Anterior Superior Iliac Supine
Avg	Average
BA	Bilateral asymmetry
Bi	Bilateral
BMI	Body Mass Index
BW	Body weight
CCD	Calf circumflex discrepancy
CKC	Close kinetic chain
Cm	Centimetre
Con	Concentric
CT	Contact Time
CV	Co-efficient of Variation
DF	Dorsiflexion
Ecc	Eccentric
EMG	Electromyography

Abbreviation	Full Definition
F	Female
H/Q ratio	Hamstrings (Con-phase) / Quadriceps (Con-phase) ratio
FT	Flight Time
H	Hamstring muscles
ICC	Intra-Class Correlation Co-efficient
Kg	Kilogram
Km/h	Kilometre per hour
LLD	Leg length discrepancy
L	Left
M	Male
M	Metre
Max	Maximum
MMT	Modified Thomas Test
NFPT	Neuromuscular functional performance test
OKC	Open kinetic chain
PT	Peak Torque
Q	Quadriceps muscles
ROM	Range of motion
R	Right
s	Second
SEM	Standard error of the mean
SF	Step Frequency
SL	Stride Length
ST	Stride Time

Abbreviation	Full Definition
StdBWD	Standing body weight distribution
SWT	Swing Time
TCD	Thigh circumflex discrepancy
Uni	Unilateral
vGRF	Vertical ground reaction force

Glossary of Terms

Active knee extension (AKE) test involves subjects lying supine with tested thigh aligned vertical and the subjects actively extend the limb as far as they could. The angle (°) of the tibia relative to the vertical at this point is a measure of hamstring length.

Measurements of anthropometric are sets of non-invasive techniques, that determine individuals' body fat structure by quantifying and evaluating specific dimensions of the human body, such as weight and height; the circumflexes of some parts of the body (i.e. thigh, arm, chest, etc.) and; thickness of skin-fold.

Peak torque of concentric knee extensor (Nm) is the gravity corrected peak torque recorded from five repetitions of isokinetic concentric knee extension at 60°/s.

Peak torque of concentric knee flexor (Nm) is the gravity corrected peak torque recorded from five repetitions of isokinetic concentric knee flexion at 60°/s.

Contact time (s) is the amount of time required to complete a full stance phase of one limb in a gait cycle. When performing a normal walking gait, the contact phase is about sixty percent of the gait cycle (Figure 1.5).

Countermovement jump is of which the jumper started from an upright standing position with both hands holding a wooden stick across the shoulders then, performs a preliminary downward movement by flexing both hips and knees, then immediately after that extends the knees and hips once again to jump vertically up off the force plates. The 2-legged counter movement jump in this study was performed using two adjacent force plates to measure the ground reaction force independently from each foot.

Gait cycle is defined as when a person is walking and one of his limbs contact the floor during the heel strike then contacting the floor once again. The gait cycle consists of two phases; stance phase when which the limb (foot) touches the floor and, swing phase when the limb is off the floor.

Knee flexion/extension ratio is the ratio between isokinetic concentric peak torque of the knee flexor divided by the isokinetic concentric peak torque of the knee extensor at 60°/s.

Modified Thomas test (MMT) is a test used to assess the flexibility of the quadriceps muscle (quads). Subjects were asked to lie down on supine position and, at the far edge of the plinth and, keeping both legs hanging freely. Then, the subjects were asked to bend one knee and pull it back to their chest as close as they can, using both arms while performing the test. The contralateral leg (the tested one), should remain hanged down. The lumbar spine must remain flat and in contact with the plinth during testing. The angle (°) of knee flexion represents the passive length of quadriceps muscle.

Running gait is a locomotion phase that starts when a person is walking without double supporting his lower limbs. When increasing the speed in running gait the swing phase increases and that consequently decreases the stance phase.

Stride length (m) is the distance between the point of first contact of one foot and the point of first contact of the same foot. When performing a normal gait, the right and left stride lengths should always be identical.

Swing time (s) is the amount of time required to complete a full swing phase of one limb in a gait cycle. When performing a normal walking gait, the swing phase is about forty percent of the gait cycle (Figure A).

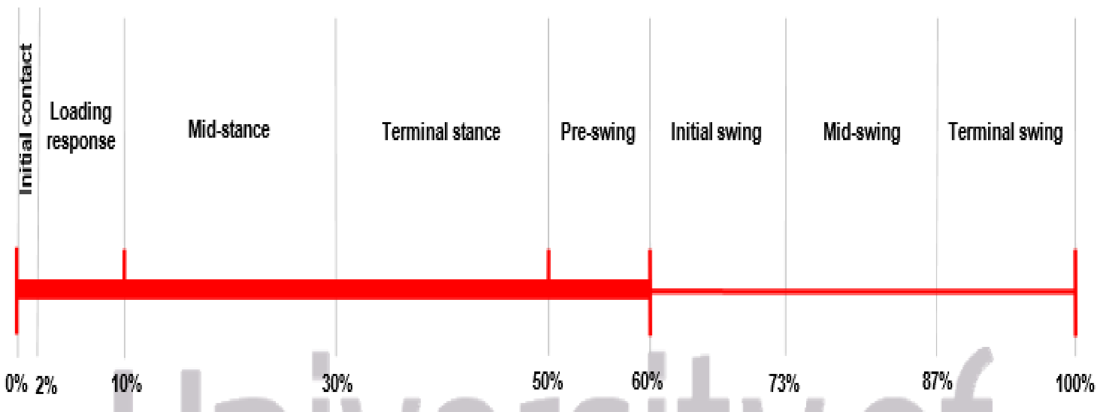

Figure A: Sub-divisions of gait cycle (Baker, R. 2013)

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Acknowledgements

I would like to thank firstly and foremost my supervisors Dr Philip Graham-Smith and Dr Paul Jones for their endless support, guidance, training, help and advices in the clinical tests and data analysis used in this research.

I would like also to appreciate the assistance and help during data collection and handling at various times of research to Hannah Gillard, Holly Calvert, Michelle McManus, Steve Horton and Laura Smith as well as the subjects participated in the studies.

My sincere gratefulness also goes to the University of Salford for providing me all equipment required to accomplish my studies.

A special thanks to the Ministry of Higher Education of the Kingdom of Saudi Arabia for sponsoring my expenses over the past few years.

Lastly, I would like to thank my beloved family; Mum, Dad, My wife Areej, Faisal, Hadeel, my bro & sisters for their beloved-support in the last few years.

The thesis is dedicated to the memory of Mohammed A. Al-Modhyan (1920-1987).

Abstract

An investigation into the relationships between strength, flexibility and anthropometric discrepancies, on lower limbs asymmetry in athletes

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Assessment of bilateral asymmetry (BA) in lower-limbs is crucial in the field of sport rehabilitation as it stands on the physical capabilities of athletes. Clinicians, in their daily practice, aim to objectively standardise their measurements when assessing athletes' performance or produce norms. Such norms, enable assessors to track athletes' performance in order to optimise it or on the other hand, to correct their BA as precautionary measure from risk of injury due to improper loading on the musculoskeletal system. Therefore, four main studies were conducted in this thesis to investigate the relationship between key criteria in lower limbs. The first study has sat thresholds for BA and once exceeded the athlete is doomed to be asymmetric. Thresholds were calculated based on the average of absolute asymmetry value percentage (AAV%) in sub-elite athletes [n=139]. An auxiliary study [n=63] was conducted within study one to examine the effect of different loads on the criteria of countermovement jump (CMJ) across jump sets. In study two, threshold norms of elite-athletes were established for four sport-specific groups and, a novel descriptive statistical approach (threshold boundary) was executed to examine the differences between them. In study three [n=144], the relationships between the criteria of CMJ and key criteria in lower limbs were examined based on a novel descriptive statistical approach called agreement in diagnosis of asymmetry. Furthermore, an investigation was conducted also, to examine the effect of manipulating leg length on the force platform profile across different sets of CMJ trials. Lastly, in study four, an investigation was conducted to examine the association between two functional tasks (CMJ and running) by using the asymmetry agreement statistical methodology [n=144].

BA were found throughout all tests and was clinically diagnosed using threshold percentage (Threshold% = mean of AAV% + SD). Moderate to high levels of association were found between criteria. The results from this thesis (0.8-38.1%) indicate that arbitrary percentages of 15% for BA in lower limbs found in literature do not reflect typical thresholds in athletes . Lastly, future studies should be conducted to define how detrimental these asymmetries in term of performance and injury risk.

Keywords: biomechanics, asymmetry, imbalance, athletes, lower limbs and threshold.

1.0 INTRODUCTION

Bilateral asymmetry (BA) is a term frequently used in the fields of sport rehabilitation, to describe any substantial deviation from normative data found in anthropometric, range of motion functional performance tests and muscle performance differences between lower limbs (Grace et al., 1984; Schlumberger et al, 2006). Limb dominance (Gabbard and Hart, 1996), previous injury (Ferber et al., 2004; Lawson et al., 2006; Newton et al., 2006), geometrical differences in bone development (Bluestein and D'Amic, 1985), neural innervations (Garry and Franks, 2004; Lawson et al., 2006), inadequate or incomplete rehabilitation program (Ferber et al., 2004), and specific motor demands of different sports and training methods (Krawczyk et al., 1998; Leroy et al., 2000; Newton et al., 2006) have been suggested as possible reasons for the development of BA among colligate and elite athletes. Asymmetry in strength, flexibility and anthropometric between lower limbs may affect performance in functional tasks (Croisier et al., 2002; Young et al., 2002; Lawson et al., 2006) and also could increase incidence of injury (Ekstrand and Gillquist, 1983; Knapik et al., 1991; Yamamoto, 1993; Orchard et al., 1997; Croisier et al., 2002; Croisier et al., 2003; Murphy et al., 2003; Zifchock et al., 2006; Croisier et al., 2008). Certainly, differences between lower limbs have been found in many athletic populations (Masuda et al., 2003; Rahnama et al., 2005; Newton et al., 2006; Zakas, 2006; Gioftsidou et al., 2008).

Moreover, the measurement and analysis of bilateral asymmetry for key criteria in lower limbs is therefore important, especially for athletes during their preseason and within season screenings aiming to reduce the risk of non-contact injuries that may occurred during training or competition (Croisier et al., 2003; Croisier et al., 2008), to quantify the functional deficits from injuries and/or surgeries (Dvir, 2004), to monitor the effectiveness of sport rehabilitation programs (Mayer et al., 2003) and to decide whether an athlete is ready to return to competition (Clark, 2001; Wilk et al., 2003).

Furthermore, excessive loadings through tissues were thought to be highly associated with non-contact injuries. As loading characteristics could vary based on the pattern of loading (Unilateral vs. Bilateral) or loading magnitude or frequency of repletion or type of loading (i.e., compression, torsion, etc.,). However, these loadings could occur as multi-factorial causes (Figure 1.1). For example, during a soccer game, the peak torque of knee extensors and flexors decrease in the second half when compared to the first one and that due to the muscles started getting fatigued (Cohen et al., 2014). This situation caused as a result of the alteration of energy synthesis from being aerobic to anaerobic. Such alteration, creates the production of lactic acid between the muscles fibres and that would lead to substantial deterioration in the quality of movement (Rahnama, Reilly, Lees and Graham-Smith, 2003). If high intensity movement continues, excessive and or abnormal loading patterns may arise leading to a greater potential for injury. Another example to illustrate the aforementioned technique to optimise the quality of performance is, controlling the limb's movement over stretched muscles during kicking a placed ball (Graham-Smith and Lees, 2002) as such corrective techniques would allow athletes to safely repeat particular movements with the least possible load over their musculoskeletal structure. Moreover, one of the extrinsic factors professional athletes consider in each sport is, to follow certain techniques to minimise the effect of muscles fatigue when competing (Newton et al., 2006). Thereby, technique errors are widely addressed by coaches as it works parallel with aims of reducing risk of injury.

Biomechanical mal-alignments or abnormalities could lead to serious deterioration in the quality of athletic performance (Greene et al., 2009), as it may cause improper weight shifting of the centre of gravity leading to asymmetric power production of both lower limbs or between agonist and antagonist muscle groups. A recent study (Hart et al., 2014) has examined how bilateral asymmetry could affect performance in soccer players and, found significant relationship between the lean mass of muscles with the accuracy of kinking a ball as athletes with larger lean mass muscles had better accuracy in their shots. This is particularly the case for bilateral movements, such as bilateral-countermovement jump (CMJ) or squats. Bell et al., (2014) has also found a significant correlation between the lean muscle mass of pelvis, thigh and leg shank with the asymmetry in performance during countermovement jumps and stated that an asymmetry of greater than ten percent is problematic as asymmetry in power could decrease performance. Thus, the body encounters such BA by providing a protective mechanism/technique by the form of compensatory movements which attempted to address the weight distribution back at the base of centre of gravity (i.e. when there is minor leg length discrepancy between both lower limbs, the hip tilts to level both iliac crest in the coronal plane) or by generating asymmetrical power from the muscles when lifting weights during sport activities. Such compensation will amplify the overall power generation from one limb and potentially decreases the overall performance due to unequal power generation of the muscles in both lower limbs (Figure 1.1).

Consequently, the first part of model in Figure 1.1 has illustrated three factors (measured, discrete and controlled) that thought to be the main causes for developing BA in lower limbs and, each factor has a number of criteria that associated with as it can be seen in the causative factors section. As for the second part, the model has demonstrated how compensatory movements could lead toward two different outcomes as overuse of one side of the lower limbs or overloading a muscle group way over it antagonist muscle group (i.e. training the knees' extensors and flexors muscle group without considering the H/Q ratio) could lead to strenuous injury even if both muscle groups had a programmed training regime that does not lead to fatigue. With regards to performance enhancement, especially during adolescence when the athletes start building up their sport fingerprint, clinicians and couches should consider the neurodevelopmental part of the athletes during their training programmes as the desire to outshine as well as well-constructed repetition training programme could enhance performance for specific and guided movements in sport (Greydanus et. al., 2011).

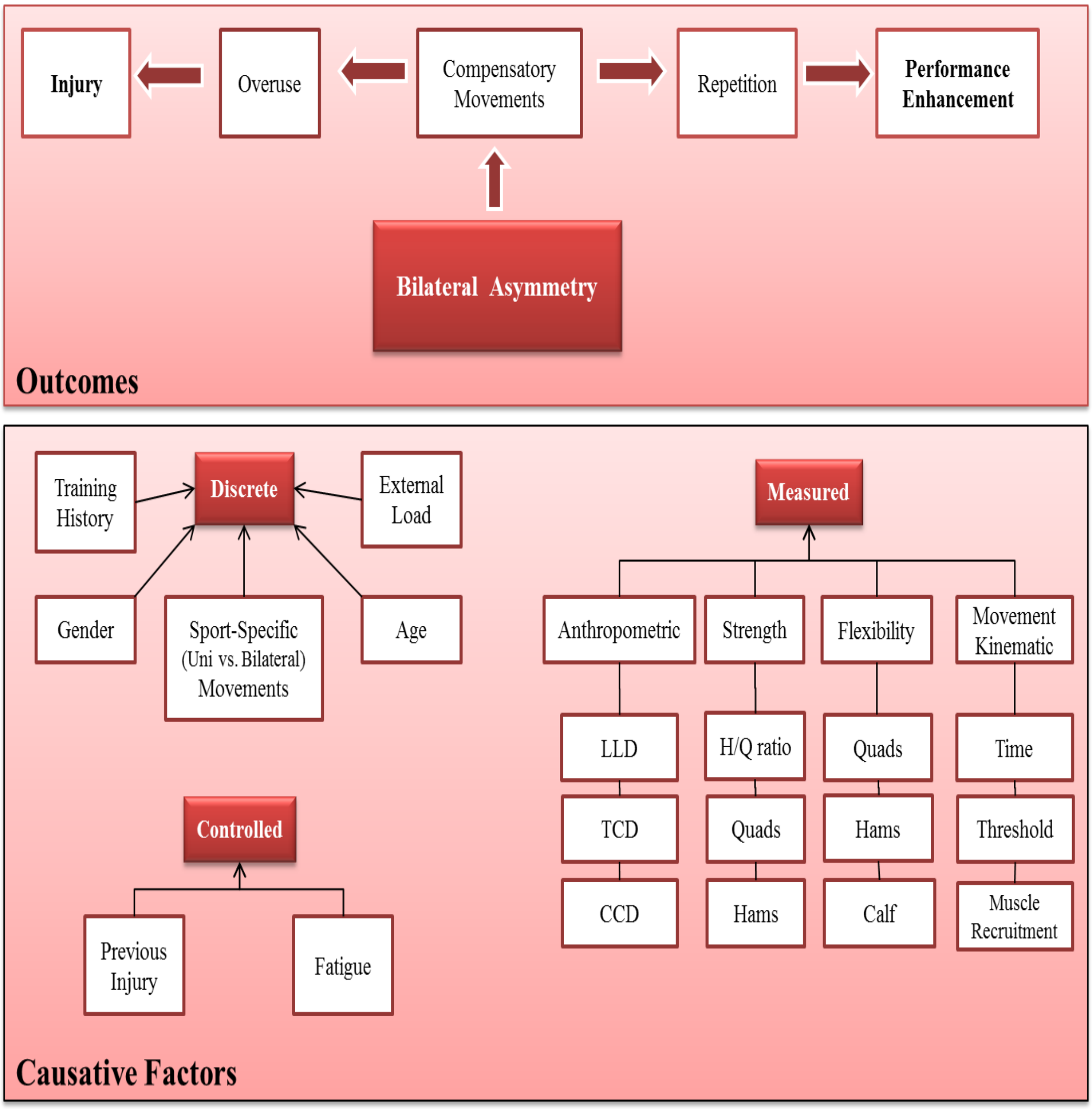

Figure 1.1: Underlying Premise of Bilateral Asymmetry

Abbreviations; H/Q= quadriceps/hamstrings muscles, Quads= Isokinetic strength test of quadriceps muscle at 60°/s, Hams= Isokinetic strength test of hamstrings muscle at 60°/s, LLD= Leg length discrepancy, TCD= Thigh circumflex discrepancy, CCD= Calf circumflex discrepancy.

Traditionally, strength and power comparisons were commonly conducted by clinicians using isokinetic dynamometry as it mimics the kicking as a function although its considered as a single-joint test (Figure 1.2) (Barber et al., 1990; Knapik et al., 1991; Wilk et al., 1994; Osterberg et al., 1998; Petschnig et al., 1998; Theoharopoulos et al., 2000; Croisier et al., 2002; Masuda et al., 2003; Rahnama et al., 2005; Newton et al., 2006; Impellizzeri et al., 2007; Gioftsidou et al., 2008). The advantage of using dynamometers was that various torques and related variables can be reliably obtained. However, the majority of these dynamometry devises can perform an isolated isokinetic muscle action, neither of which, was specific to most sport activities (Gray, 1992; Lephart et al., 1992). This can become problematic when isokinetic testing is solely used to determine an individuals' readiness to return to normal activity levels after an injury, as several investigations have yielded poor relationships between open kinematic chain (OKC) (i.e., isokinetic strength testing) and neuromuscular functional performance tests (NFPT) (i.e., hopping) (Lephart et al., 1992; Mognoni et al., 1994; Wilk et al., 1994; Murphy and Wilson, 1996; Ostenberg et al., 1998).

As a Consequence, diagnostic assessment methods for BA using closed kinetic chain (CKC) movements, such as hopping, jumping and landing tests were developed. Such movements were considered as multi-joint tasks and that requires precise synergy from different body components making these tasks far complex from a single-joint tests (Figure 2.1). These tests have been proposed as a superior assessment tool when evaluating athletes, as their movements are more similar to sport-specific tasks (Augustsson and Thomee, 2000; Newton et al., 2006).

However, one of the limitation of functional testing is, the cause of asymmetry as its masked by multi-joint and multi-factorial issues contributing to the performance. Therefore, potential underlying causes of asymmetry, such as joint ranges of motion (ROM), leg length discrepancy (LLD), lean mass asymmetry (circumflexes of thigh and calf muscles) or strength imbalances within specific muscle groups would be considered in order to plan corrective recommendations. Furthermore, bilateral strength differences of the same muscle measured by isokinetic strength testing might not be verified by functional performance tests, since other muscle groups might compensate for these differences and different assessment methods may lead to different diagnoses (Jones and Bampouras, 2010).

Figure 1.2: Subject performing isokinetic strength testing (Jones and Bampouras, 2010)

There is a distinct lack of research investigating anthropometric factors such as LLD, ROM, and lean mass circumflexes on how they might affect bilateral asymmetry. Lean mass asymmetry may be a result of prolonged lengthening or shortening of a muscle group as a result of a LLD. The size of the muscle may also affect asymmetry as a muscle with a larger mass and cross sectional area tends to be stronger than a muscle with a smaller lean mass (Yoshioka et al., 2010). Performing anthropometric measures such as leg-length, muscle circumference and flexibility could help explain why one limb may over compensate for the other if one leg is slightly longer that the other or the cross sectional area of one muscle is larger than the opposing muscle.

Although the two-legged CMJ (Figure 1.3) is believed to be an important functional movement as it serves as a multi-joint CKC exercise, isokinetic tests using dynamometer is still one of the most commonly applied methods for strength assessment during the rehabilitation programme and assessment of athletes in lower limbs (Ostenberg et al., 1998; Zakas et al., 2006; Croisier et al., 2008).

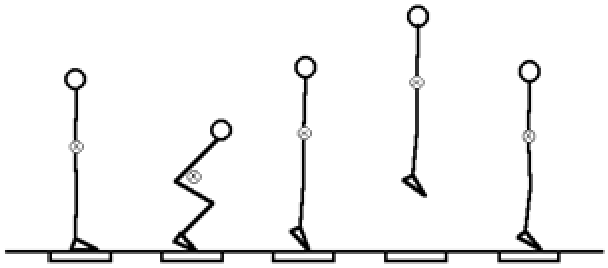

Figure 1.3: Sequence of actions in a countermovement jump (Linthorne, N.P. 2001)

There is a distinct lack of research regarding the best choice of test to determine BA (i.e., one or two-legged CMJ, OKC or CKC). The influence of load on CMJ and its effect on the diagnosis of lower limb BA also needs to be clarified. Newton et al., (2006) compared several protocols to assess BA including squats, vertical jumps, isokinetic dynamometry and a 5-hop test in 15 female softball players. It was found that all tests detected muscle imbalances related to sport-specific demands, but with no correlation between all tests. A pre-selected load of 80% of the subject's one repetition maximum was chosen for the bilateral squat test. Using just one load may not be sensitive enough to detect asymmetry and different athletes may respond differently to lighter or heavier loads. Little is known about the effects of using different loads on BA or the exact load when asymmetries occur.

However, there is a more fundamental issue that has not been addressed in the literature; for all of the aforementioned tests, what is the critical value of asymmetry that diagnoses an asymmetry between lower limbs? There is a general theory that bilateral differences of greater than 15% are relevant for hop and jump tests (Noyes et al., 1991; Petschnig et al., 1998; Clark, 2001; Impellizzeri et al., 2007), and isokinetic measures (Brown and Whitehurst, 2000; Croisier et al., 2003; Croisier et al., 2008). Nevertheless, due to few studies (Impellizzeri et al., 2007; Croisier et al., 2008; Fousekis et al., 2012) that have identified definitive cut-off percentages or what is a “normal” or “absolute” difference between limbs, it is still unknown as to what would classified an asymmetry. Thereby, it is imperative to establish norms for bilateral asymmetry in order to statistically diagnose whether an asymmetry in performance is significant or not. Clearly the early mentioned nominal value of 15% cannot just be assigned to other measures such as leg length, as its unlikely that athletes have such large discrepancy between their limbs.

With contradictions in the literature, it was important to investigate the relationship between different kind of attributes (CMJ, anthropometric measurements, NFPT and isokinetic strength) and their ability to detect BA in lower limbs. The identification of BA appears to be highly dependent on research methodology (Schot et al., 1994), it is important to investigate the concordance of identification of lower limb BA between the various testing methods. Previous research (Kovaleski et al., 2001) has performed correlation analysis to examine relationships between OKC versus CKC measurements which allowed investigating the relationship between discrete (or static) tests only. Such a limitation would hinder practitioners and healthcare providers from using the outcome measures developed from those studies as a diagnostic tool for asymmetry as it investigates relationships between static and dynamic tests or single and multi-joints task. Therefore, it was important to conduct thorough investigations into BA in a more structured procedure. Such structured procedure would allow measuring all the causative factors and then, comparing these factors against BA in a functional performance behaviour (running: which represent unilateral asymmetry behaviour / jumping: which represent bilateral asymmetry behaviour) and that, which most athletes either do during competition or as part of their training. Whilst this is interesting, research into BA has failed to adopt a multi-factorial approach that helps to identify the causative factors for asymmetry, nor have examined the effect of different loads on a specific factor (for example, CKC measurements) as well as no study has yet examined the "agreement" in clinical diagnosis of asymmetry between different modes of testing.

Lastly, many studies have used the CMJ as a bilateral functional behaviour CKC test (Baker et al., 2001; Ugarkovic et al., 2002 Newton et al., 2006; Impellizzeri et al., 2007). However, none have looked at how BA manifest itself in cyclical unilateral movements (i.e., running). Thus, a new unilateral functional behaviour test would be a key variable to be administered as part of BA functional behaviour analysis variable in this thesis. Therefore, athletes were asked to run on a treadmill while high speed cameras from different angles recorded their gait for any unilateral asymmetry.

1.1 Aim of Research

The aim of this thesis is to establish a 'typical' cut-off asymmetry percentage for key criteria in lower limbs that, diagnose bilateral asymmetry in sub-elite athletes involved at a wide array of sport activities. For example, a 15% of BA difference in LLD is a huge difference as it could represent a difference of 15cm between lower limbs. Thus, this novel assessment tool would identify specific threshold values for each criterion (Chapter 4). To achieve such aim the following objectives need to be accomplished:

- To identify typical bilateral asymmetry differences between lower limbs irrespective of classification of left versus right, dominant versus non-dominant using the absolute mean difference.
- To compare the identified thresholds with current proposed thresholds found in the literature (15%).

Subsequently, these cut-off asymmetry percentages were thought-provoking to investigate for more sport-specific threshold percentages. Thus, four sports were chosen to generate sport-specific cut-off percentages by recruiting elite-athletes from a selected sport groups (chapter 5). The objectives of this study were as follow:

- To identify statistically, cut-off percentages based on clinical examinations for key criteria in the lower limbs for sport-specific groups of elite-athletes' population.
- To investigate the generated parameters of all tested factors and compare them across all groups to examine, if distinct repetitive movements could associate with noticeable asymmetry differences in each sport group.

In consideration of understanding the cause and effect relationship between the static, dynamic and single-joint tests and how they can influence the bilateral asymmetry of the multi-joint and functional tasks of an athlete (bilateral and/or unilateral), an investigation was undertaken to look at the association/correlation between six different kind of attributes; A) Strength imbalances, B) Joint range of motion (flexibility), C) Anthropometric discrepancies, D) NFPT, E) CMJ and, F) 1LCMJ. Therefore, a number of statistical analysis methodologies were introduced to compare seventeen key variables in order to examine their influences between one another. Pearson's correlation and the association of asymmetry agreement tests

(Descriptive analysis that examines the association between two criteria. The association counts the frequency in diagnoses of asymmetry based on the thresholds. If both criteria had the same diagnosis a positive value was given and the total of like to like diagnoses were counted and divided by the number of subjects. Refer to Section 3.3.1, Equation 3) were utilised for comparison in order to address the following aims:

- To administer a new qualitative statistical analysis approach to examine the asymmetry agreement between variables and their influences to one another.
- To examine the correlation between variables and then, to investigate whether the outcome differs from the result of the association of asymmetry agreement.
- To investigate asymmetry agreement between various modes of bilateral test of asymmetry (i.e., OKC versus CKC, 1LCMJ versus CMJ).

Nevertheless, gait can be altered by a great number of compensatory movements forcing the athlete to consume more energy which may deteriorate optimum performance or being at risk of injury due to overstressing the musculoskeletal system. Thus, it was crucial to introduce further parameters that look into a number of key criteria of unilateral movements of each leg during running and, examine it asymmetry agreement with another functional task. Thus, the objectives of this study were as follow:

- To determine normative for selected parameters in running gait.
- To examine the level of association of asymmetry agreement between the CMJ and running gait criteria (chapter 7).

The knowledge gained from establishing exact cut-offs percentages for specific lower limb characteristics would potentially increase the clinicians' ability to diagnose and understand the causative factors of athletes' exhibiting BA. Knowing what lower limb variables have the potential to differ substantially from side-to-side will assist clinicians and researchers in determining the extent to which there is potential injury risk or whether a single limb versus both limbs should be measured in pre-season screenings and prospective study designs. Established more statistically sound critical cut-off criteria in the form of the "absolute asymmetry value percentage" (AAV %) could be eventually more precise and meaningful assessment tool for physiotherapists and strength and conditioning coaches in diagnosing asymmetry in lower limbs.

Understanding the causative factors associated with lower limb asymmetry would elaborated into establishing a more targeted assessment programme that rectifies asymmetry or modify training regimes to offset the exacerbation of bilateral asymmetry on athletes' performance.

1.2 Research Questions

Four research questions have been generated from the introduction:

Q1: Do different criteria have their own unique cut-off percentages?

Q2: Could each Sport-specific group of athletes have their own BA profile due to their distinct prolonged loading characteristics during training and competition?

Q3: Is there any associations based on the asymmetry agreement test, between criteria of countermovement jump with key criteria in the lower limbs?

Q4: Is there any associations based on the asymmetry agreement test, between the criteria of countermovement jump and the criteria of running gait?

Four studies were conducted to answer the aforementioned questions respectively and, targeting the aim of this thesis as follow (chapters 4-7);

Chapter 4.0: Reliability of measures used to assess and diagnose lower limb asymmetry.

Synopsis: BA imbalances are examined using a variety of testing methods and modes. Surprisingly, there is no definitive criterion for the clinical diagnosis of asymmetry. Moreover, there are several issues with respect to how a 'normal' difference between limbs is determined. Previous researches (Theoharopoulos et al., 2000; Newton et al., 2006; Impellizzerri et al., 2007) that has compared left and right limbs tend to find close to zero 'mean' differences (as negative and positive differences cancelled out themselves) and tend to adopt measures of variance between subjects as the criterion.

These do not provide a relevant measure of a ‘typical’ difference. The aim from the study is to establish true values for typical levels of asymmetry [n=139] and introduce the term ‘absolute asymmetry value’ (AAV). This approach de-classifies a limb from being ‘left’ or ‘right’ and ‘dominant’ or ‘non-dominant’. Before executing the main study in this chapter a pilot study was conducted in order to produce preliminary data for testing the reliability (inter-trial) of key criteria in lower limbs as well as establishing AAV% by analysing sixty-three mixed-athletes (Elite and colligate) from both genders (Poster presentation (Appendix E) has been published in the ESBiomech 2013 in Patras, Greece).

Chapter 5.0: Establishing norms for bilateral asymmetry in lower limbs for elite-athletes in four specific sports.

<u>Synopsis:</u> Utilising the AAV% for specific lower limbs criteria would increase the clinicians’ abilities to diagnose BA as well as identifying the potential risk of injury. Thus, this study has established BA norms for four sport-specific group for key criteria in lower limbs. Knowing what lower limbs variables have the potential to differ substantially from side-to-side, would assist clinicians and researchers to determine the extent to which there is a potential to improve athletes’ performance. Finally, the focused sport-specific groups of elite-athletes; Cricket [n= 11], Rugby [n= 38], Athletics [n= 10] and Soccer [n= 20].

Chapter 6.0: Agreement between attributes associated with bilateral jump asymmetry

<u>Synopsis:</u> This study was divided into two parts. The population of the first part was generated retrospectively from a mixture of elite and colligate athletes [n=144]. The purpose from this study was to examine the relationships between a numbers of key criteria in the lower limbs and how they influence one another. Whereas the second part of this study has investigated the influence of rectifying the leg length on the criteria of

countermovement jumps [n=10] by manipulating the height of the force platforms on both sides and, examining any developed rectification in the force plate profile.

Data handling: A qualitative statistical analysis test was introduced by comparing the level of asymmetry agreement between variables. Association agreement percentage around 66.6% (2 out of 3 participants) was classified as having a low association between two variables where as 80% (4/5 participants) and above was considered as high association. Seventeen criteria from six different kinds of attributes where assigned to identify the influence of key criteria in the lower limbs and how they influence one another using the association of asymmetry agreement. Then, Pearson's r correlation test was performed on the same set of data to compare the outcomes with newly proposed statistical analysis (the asymmetry agreement test). Previous studies (Newton et al., 2006; Impellizzerri et al., 2007; Menzel et al., 2013) have compared limited numbers of single-joint and functional tasks in lower limbs (the only similar comparisons between the two studies were the strength of the quads and hamstrings muscles at 60°/s with the maximum forces of CMJ and 1LCMJ) using a small sample size [n=14] thus, this novel methodology (asymmetry agreement test) would suggested a more meaningful statistical comparisons when examining the influence between several key variables in the lower limbs based on a large sample size.

Chapter 7.0: Investigation into asymmetrical analysis on two functional tests: running gait and countermovement jump.

Synopsis: Running is an activity that the majority of athletes participate in, either as part of their sport or as a part of their training regime. It is a cyclical activity in which the limbs are loaded unilaterally. This study helps to address whether the diagnosis of BA in discrete tests manifest themselves in a more dynamic and functional skill pertinent to the majority of athletes. Previous research (Cavanagh et al, 1977; Theoharopoulos et al., 2000; Newton et al., 2006; Impellizzerri et al., 2007; Jones & Bampouras, 2010) has investigated relationships between OKC and CKC tests, but with examining only a limited number of causative factors of lower limb asymmetry as well as not establishing any kind of a cause-effect relationship (Figure 1.4).

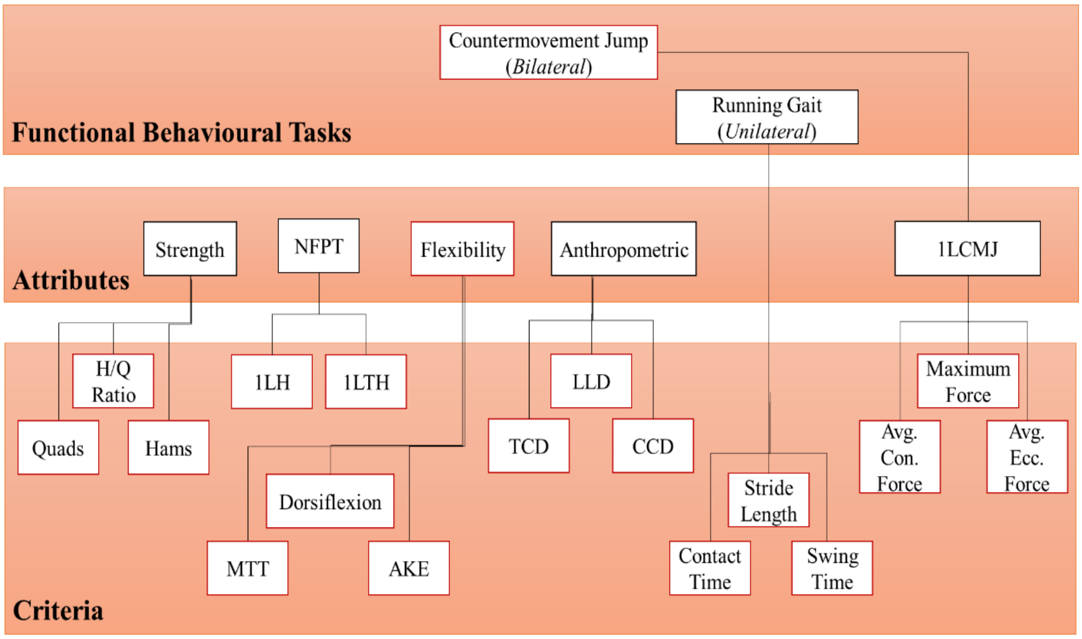

Figure 1.4: Factors of functional performance (potential Cause ↔ Effect relationship).

Abbreviations; H/Q= quadriceps/hamstrings muscles, Quads= Isokinetic strength test of quadriceps muscle at 60°/s, Hams= Isokinetic strength test of hamstrings muscle at 60°/s, Dorsiflexion= Ankle dorsiflexion, MMT= Modified Thomas test, AKE= Active Knee Extension, LLD= Leg length discrepancy, TCD= Thigh circumference discrepancy, CCD= Calf circumference discrepancy, 1LCMJ= one-legged countermovement jump, Avg. Con. Force= Average Concentric Force, Avg. Ecc. Force= average eccentric Force, NFPT= Neuro Functional Performance Test, 1LH= One-legged hop, 1LTH= one-legged Triple Hop.

Data handling: The same qualitative analysis used in the previous chapter (chapter 6) was utilised again to investigate the agreement between CMJ and running gait only. One hundred and forty-four academy athletes were tested to examine the agreement between criteria of both attributes. The cut-off percentages (AAV %) methodology was executed again in this study to identify the athletes who exceeded the threshold and diagnosed to be abnormally asymmetric. Lastly, it is advisable for athletes who being diagnosed with multiple asymmetries, especially if in both functional tasks, to be closely monitored throughout the season for any deterioration in their performance as they might be at risk of injury if their asymmetries started to accumulate additionally.

1.3 Limitations

One of the limitations of this research is that the sample size for all studies except study one, was not evenly distributed between males and females. Consequently, the absolute asymmetry values may not be accurately applicable to female athletes' population and, this would benefit from further research. No evaluation of the effect of age or training history on asymmetry was made and this would be also beneficial for future research. Furthermore, due to time constraints, the isokinetic strength tests examinations of ankle plantar/dorsiflexion, hip flexors/extensors were not performed and that leaves only the knee flexors/extensors muscle groups being examined. Lastly, this research did not look at muscle recruitment when performing the tested tasks due to the considerable time consumed when installing the electromyography device on the subjects.

In order to increase the accuracy of the anthropometric measurements and joints angles one researcher performed the same testing for the participants. All participants were fresh at the day of testing to control the effect of fatigue during testing and, all performed tests were at maximal effort. Injury history was controlled by assumed that subjects reported correct information regarding their history at the day of testing and all injured subjects were excluded from the analysis. Moreover, the familiarisations for all tests were performed at the day of testing and, a randomised sequence was performed for the bilateral asymmetry analysis bundle throughout all studies due to the large number of participants in each booked session.

Lastly, the next chapter has reviewed all the current literature in the bilateral asymmetry that is related to lower limbs. The university of Salford research engine as well as google scholar were utilised to search for the correspondent topic using a number of keywords such as; bilateral asymmetry, bilateral, asymmetry, asymmetry index, lower limb, countermovement, isokinetic, anthropometric, flexibility, hop test, athlete and running gait.

2.0 LITERATURE REVIEW

There are many theoretical origins of BA and inconsistencies in the literature regarding the existence of bilateral symmetry or asymmetry in functional and physical characteristics, which will be explored in this review. The focus was directed towards the lower limb, the CMJ, isokinetic strength testing and NFPTs. Therefore, the literature review began by highlighting the underlying premise of BA and how this along with other associated mechanisms, may predispose athletes to injury. The model presented earlier (Figure 1.1), outlines the clinical relevance of such an approach which can be found in section 2.1. The definition of BA was introduced and how researchers diagnose lower limbs in terms of symmetry and asymmetry (Section 2.2). The variables were explained as of how data being collected, in order to diagnose BA based on the theories developed by researchers (Section 2.3). The association between asymmetry on performance and the potential increased risk of injury was investigated in section 2.4. Review for certain values of BA was conducted to indicate thresholds of asymmetry (Section 2.5). The procedure used in analysing the data to gather information about asymmetry was reviewed (Section 2.6). The last section of the literature review (Section 2.7) has clinically evaluated other asymmetry studies in term of the targeted population (non-injured/injured or elite/recreational athletes), kinds of examination (number and types of criteria) and the statistical approaches (asymmetry indexes) when examining bilateral asymmetry.

The aim of the literature review was to highlight the limited research and understanding of bilateral asymmetry as well as the mechanisms surrounding its relationship with performance and potential risk of injury. This research aims to present a model that helps to classify the potential factors associated with lower limb asymmetry in athletes. Several criteria were identified to examine BA in lower limbs in section 2.3 and, those criteria were analysed in the literature as showed in section 2.5 however, it was not applicable to compare findings that diagnose asymmetry between studies due to the different methodologies (different asymmetry indexes, statistical analysis tests and sets of tested criteria) used to identify asymmetry (2.6). Thus, the model of bilateral asymmetry analysis bundle presented in chapter 3, aims to provide accurate statistical approach to classify athletes for BA. Moreover, the statistical analysis methodology presented in section (3.3.7), would aid clinicians during the pre/within season screening by providing then with a robust tool to trigger asymmetry in lower limbs.

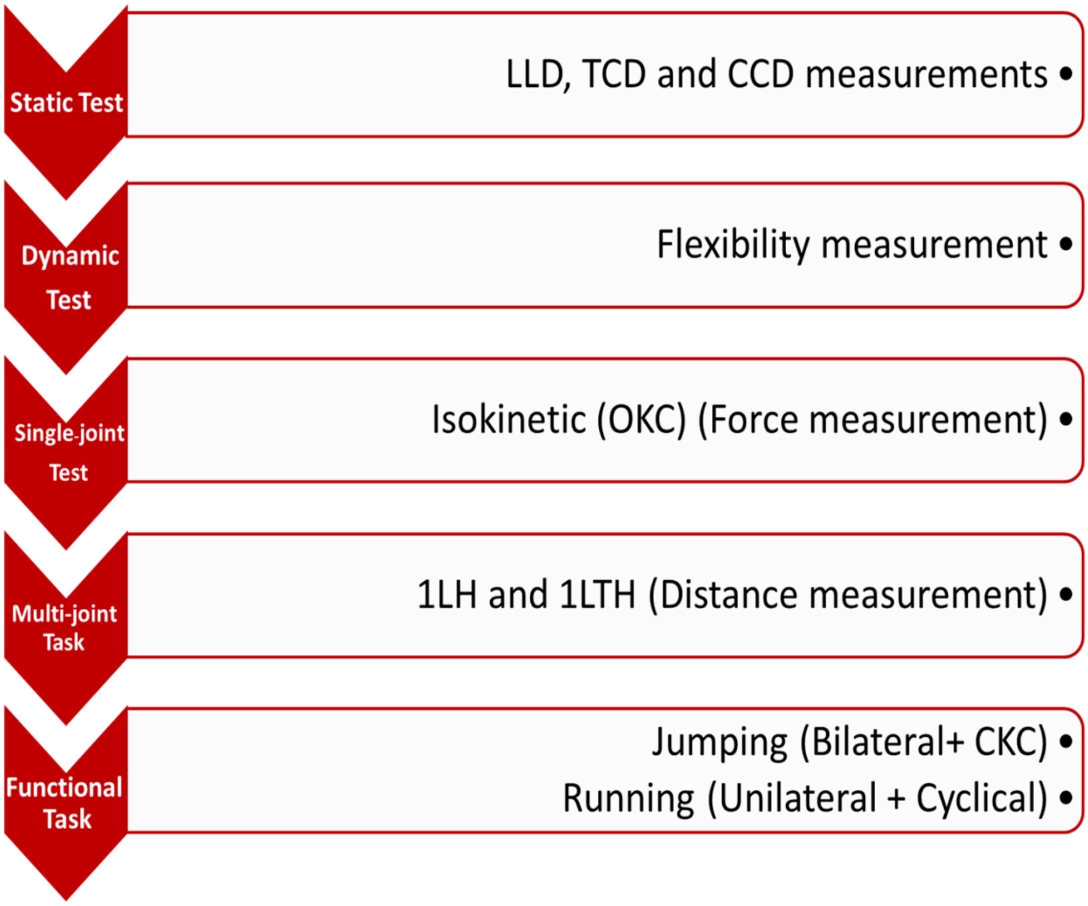

Figure 2.1: Continuum of Functionality Diagram.

Abbreviations; LLD= Leg length discrepancy, TCD= Thigh circumflex discrepancy, CCD= Calf circumflex discrepancy, 1LH= One-legged hop, 1LTH= one-legged Triple Hop, OKC= Open kinematic chain, CKC= Closed kinematic chain.

2.1 Terminology

It is important to state that the terms “dominant” and “preferred” are used interchangeably throughout the literature. Additionally, terms such as “laterality” and “asymmetry” have also been used in similar contexts. However, these terms have different definitions. In order to understand the importance of evaluating an absolute difference between lower limbs, rather than dominant/non-dominant or preferred/non-preferred a distinction between these terms is necessary.

Harris (1958) defined laterality as the preferred use and superior performance of one side of the body compared to the other side. Since then, other reviews have traced the preferential use of one side of the body, to the brain (Coren and Porac, 1978; Peters, 1988). Touwen (1972) defined laterality as a phenomenon that occurs in an organism with paired faculties, whereby the performance of certain tasks is better on one side. Touwen (1972) also stated that laterality is an asymmetrical function and he defined dominance as the central nervous system (CNS) phenomenon in which one side of the brain plays a major role in a specific function. Thus, preference is the inclination to use one side of the body instead of the other and should not be confused with dominance (Kellor et al., 1971). This is a major problem associated with asymmetry studies. The reasons why one prefers to use one side instead of the other are still controversial; however, dominance and laterality may influence one’s choice but this is not definite. Dominance should therefore not be used synonymously with laterality because the former refers to a CNS phenomenon and the latter refers to a peripheral phenomenon. Another preferred reference to demonstrate laterality between lower limbs was called preference as described by Zifchock and Davis (2008).

Reviewing the literature demonstrates that many studies investigating lower limb BA have defined the dominant leg as the “preferred leg to kick a ball” (Costain and Williams, 1984; Kramer et al., 1994; Wang et al., 1993; Herring, 1993; Cordova et al., 1995; Gabbard and Hart, 1996; Nyland et al., 1999; Rosene and Fogarty, 1999; Blackburn et al. 2000; Pincivero et al., 2002; Matava et al., 2002; Newton et al., 2006; Stephens et al., 2007). Furthermore, regarding countermovement jump tests, Benjanuvatra et al., (2013) has reported that differences in performance between one-legged and two-legged CMJ does not associated on the asymmetry differences found in power and strength exclusively as other attributes may also cause such variance in performance between the two tests. These studies demonstrate that researchers have used the term dominance differently in context than what has been defined, authors have used these terms without considering the definitions explained previously. Unfortunately, the majority of the research uses the term dominance when inferring that a person is more inclined to use one limb to perform certain tasks.

Whilst the semantics around preference and dominance are interesting, within a rehabilitation context it is more important to understand the effect of the potential differences in function and on loading between the limbs. In this respect the terms symmetry and asymmetry become more meaningful.

2.2 Symmetry and Asymmetry

Bilateral asymmetry (BA) is a term frequently used in fields of rehabilitation as well as performance sport and is used to describe differences between left and right sides of the body. It has been defined as an imbalance of strength, power, endurance or flexibility between the corresponding muscle groups of different extremities (Grace, 1985). A muscle imbalance is commonly described as a distinct level of muscle performance lying outside the continuum of an assessed normal physiological muscle function (Schlumberger et al., 2006). Symmetry has been defined as the perfect agreement between the actions of paired limbs (Herzog et al., 1989). The justification for perceived and implied symmetry is that it will maximise energy efficiency, whereas asymmetry in bilaterally symmetrical lower limb movements will be detrimental to performance efficiency. For example, if one designed a robot to jump as high as possible from a symmetrical stance, the robot would be designed such that the propulsion generated from each lower limb was equal. This expectation also holds true when one considers a human performing a CMJ. It is necessary to state before proceeding further that an asymmetry could be considered to be any deviation from zero (i.e. perfect symmetry) and is not clearly defined in the literature in terms of numerical value. Thus, many researchers have created indexes to describe the deviation objectively. However, there were no specific percentages given for a number of key criteria in lower limbs beside the arbitrary value of fifteen percent difference between sides that defines an athlete from being asymmetric. Furthermore, an exploration of how much asymmetry difference may affects performance was reviewed thoroughly in Section 2.5.

There were a number of studies suggested that lower limb asymmetry is common in athletic populations (Masuda et al., 2003; Newton et al., 2006; Rahnama et al., 2005; Gioftsidou et al., 2008). Asymmetry of strength and flexibility is evaluated most often (Goslin and Charteris, 1979; Holmes and Alderink, 1984; Berg et al., 1985; Knapik et al., 1991; Orchard et al., 1997; Croisier et al., 2002; Rahnama et al., 2005; Newton et al., 2006; Impellizzeri et al., 2007). Asymmetry of jumping abilities (Noyes et al., 1991; Newton et al., 2006), power endurance (Valdez et al., 2004) anatomic structure (Singh, 1970), kinematic, kinetic, and muscle activity characteristics (Goslin and Charteris, 1979; Arsenault et al., 1986; Vagenas and Hoshizaki, 1988; Herzog et al., 1989) have been also studied.

2.2.1 Functional roles of the lower limbs

Some scientists have suggested that BA may reflect differences in the functional roles of each lower limb. Using the 'kicking leg' to be the dominant leg, as many studies have, depending on the sport or activity, the non-dominant leg would become the preferred 'plant leg'. Given the repetitive activity of athletic performance, it would intuitively follow that the non-dominant limb may adapt with greater strength and balance (MacNeilage, 1991; Gabbard and Hart, 1996), whereas the dominant limb would adapt with enhanced coordination and skill (Singh, 1970; Gabbard and Hart, 1996). Kramer and Balsor (1990) suggested that this difference in volume of activity between the dominant/kicking and non-dominant leg could produce strength BA. For example, in soccer, for every kick and task to control the ball with the dominant leg, the non-dominant leg is active to produce hip and knee flexion and extension in a CKC skill during a unilateral free-weight bearing stance. Therefore, the non-dominant leg could be stronger in many athletes when tested with CMJ and 1LCMJ, due to the specificity between this weight-bearing test and the high use of the non-dominant leg for weight-bearing support that occurs during many sport-skills. Conversely, Ross et al., (2004) concluded that the kicking limb had superior thigh strength, better proprioception, and greater knee flexion than the stance limb. However, a more recent study suggests that limb dominance is related to the type of task the subject is asked to perform (Velotta et al., 2011). If the task required is manipulative in nature, the majority of subjects will rely on the right leg as the preferred or dominant leg. However, when subjects are asked to perform a task requiring whole body stabilisation, there was some shifting towards the left leg (Velotta et al., 2011).

These findings question the usefulness of reporting leg dominancy as derived from standard tests such as isokinetic dynamometry, and is a major flaw of studies such as Newton et al., (2006). It is the reason why in this study limb dominance was not evaluated – instead an alternative, statistically based asymmetry evaluation was used, the absolute mean difference between lower limbs.

2.3 Development and Sources of Asymmetries

Theories regarding the origins of how asymmetries may developed have been researched in the literature. This section will detail these sources and their influence on bilateral asymmetry in lower limb.

2.3.1 Anthropometric

2.3.1.1 Leg Length Discrepancy

Leg length discrepancy (LLD) is an example of an anthropometric source of asymmetry. In Knutson's (2005) review, it was determined that 90% of the population is affected by some degree of LLD; the left leg being anatomically longer more often. However, this does not typically lead to problems if the difference is less than 2 cm. The biomechanical effects of mild limb-length inequalities (e.g., differences <2.5 cm) have been a source of speculation. Most likely as a result of postural changes, previous reports suggested that LLDs were linked to pain and dysfunction in the knee (Mahar et al., 1985; Kujala et al., 1986; Brunet et al., 1990), hip (Gofton and Trueman, 1971; Friberg, 1983), lumbar spine (Giles and Taylor, 1981; Friberg, 1983; Brunet et al., 1990; Soukka et al., 1991; ten Brinke et al., 1999) and stress fractures (Friberg, 1982).

Several authors (Subotnick, 1976; Friberg, 1982) concur that mild LLD may be deleterious if an individual participates regularly in tasks involving repetitive mechanical loading, such as athletes in sporting activities. Subotnik (1981) stated that an uncorrected LLD can result in unilateral weakness, causing a myriad of overuse injuries ranging from greater trochanteric bursitis to plantar fasciitis. Blustein and D'Amico (1985) stated that LLD can increase energy expenditure and reduce muscular efficiency, leading to increased stress, fatigue and reduced performance.

2.3.1.2 Limb Circumference Discrepancy

The use of limb circumference measurements is routinely used to assess thigh and calf atrophy (Stoboy et al., 1968; Eriksson and Haggmark, 1979). Re-attainment of lost limb circumference is a common physiotherapy treatment goal, based on the assumption that an increase in thigh or calf circumference indirectly suggests an improvement in strength (Allison et al., 1993). The size of a muscle may have implications to force production and CMJ performance. A larger physiologic cross sectional area (CSA) may reflect an increased number of sarcomeres. This could result in a greater number of cross-bridge formations, which could increase force production. In the case of CMJ, larger muscle size on one limb may be positively associated with performance. Davis et al., (2003), measured thigh circumference as well as calf circumference and, found that as the circumference increased so did the jumping performance. Unfortunately, only one study (Masuda et al., 2003) has inspected the relationship between muscle circumference and isokinetic strength testing and found no association between them which could be due to the relatively small sample size used in the study (n=14). The CSA of a muscle is believed to be important for producing power (Tortura and Grabowski, 2002) and is proportional to the maximum magnitude of force that can develops (Murphy et al., 2002). Therefore, thigh circumference has received interest as a potential risk factor for lower limb injury with regard to the muscles' ability to stabilise and control the joint movement.

The assumed association between lean mass asymmetry and muscle torque asymmetry has been questioned previously (Cooper et al., 1981; Gross et al., 1989; Lorentzon et al., 1989). Cooper et al., (1981) concluded that TCI was not predictive of torque asymmetry. Though Cooper's study had an adequate sample size (n=64), the fact that their design included both non-injured and injured subjects leaves room for further investigation. Gross et al., (1989) reported that thigh circumference, when combined with other anthropometric and demographic variables, predicted knee extension and flexion torque production with significant statistical accuracy in healthy subjects.

Lorentzon et al., (1989) studied 18 subjects with TCD and found no significant correlations between isokinetic performance and muscle size (as determined by computed tomography) or thigh circumference measurements. In a study of risk factors for lower limb injury in 45 recreational basketball players, Shambaugh et al., (1991) found that injured athletes had greater BA in quadriceps girth (0.93 ± 0.7 cm) than uninjured ones (0.26 ± 0.5 cm). The limitations of this study were that gender was not specified and, the sample size was relatively small [n = 45].

The literature has not been conclusive about the effect of cross sectional area of the thigh and calf, with production of strength/power. However, with the introduction of the absolute asymmetry value percentage as a new method for inter-correlation between criteria, could withstand great chance to be crucial elements in including TCD and CCD in a protocol in order to assess bilateral asymmetry during a functional test (i.e. countermovement jump).

2.3.2 Strength

Asymmetrical strength across the lower limbs can be defined as the inability to produce an equal force of contraction between the muscles (quadriceps and hamstrings) of the right and left sides. Muscle strength asymmetry and imbalance between lower limbs may develop in part due to handedness, previous injury or repeated use, as in training for a specific sport (Newton et al., 2006). This has been linked to pathological conditions of the muscle groups themselves (Burkett, 1970) and various lower limb joints (Gribble and Robinson, 2009).

There is contrasting evidence in the literature in regards to lower limb bilateral strength asymmetry. Several studies have reported no significant differences in the lower limbs. Greenberger and Paterno (1995) evaluated concentric knee extensor isokinetic strength using a Kin Com dynamometer (Chattanooga Group, USA) at 240°/s in 20 male and female students and reported no significant differences in the dominant and non-dominant legs. Perrin (1986) examined bilateral concentric knee flexor and extensor isokinetic strength at 60° and 180°/s in 15 baseball pitchers, 15 swimmers and 15 non-athletes all of whom were male collegiate athletes. Results demonstrated similar peak torque (PT) values between the lower limbs during knee flexion or extension and no asymmetry was noticed among the 3 groups. This was the only study that examined isokinetic strength differences in college-aged non-athletes and athletes of different sports. Masuda et al., (2003) assessed isokinetic hip and knee strength and revealed that no differences between the dominant and non-dominant leg in elite soccer players. Agre and Baxter (1987) and Ostenberg et al., (1998) found no difference between the dominant and non-dominant leg in men and women soccer players. Newton et al., (2006) found no significant difference in PT between the right and left legs at either 60°/s or 240°/s for isokinetic knee flexion or extension strength however, a significant difference was found when comparing the strength of the dominant and non-dominant limbs. Lucca and Kline (1989) tested concentric knee extensor and flexor strength of 54 male and female students using the Cybex II isokinetic dynamometer (Cybex, Division of Lumex Inc., Ronkonkoma, USA) at 60, 120 and 240°/s and reported no significant differences between legs.

However, several studies have reported significant differences in the lower limbs. Chin et al., (1994) evaluated isokinetic knee extensor and flexor strength on a Cybex II isokinetic dynamometer at 60°/s and 240°/s. They reported stronger knee flexors in the dominant leg compared to the non-dominant leg with no difference in the extensors. Kellis et al., (2001) measured concentric and eccentric knee extension and flexion PT at 60°, 120° and 180°/s using the Cybex dynamometer in 158 soccer players, and found a significantly stronger preferred leg than the non-preferred leg, when leg preference was determined with the ball kicking task. Siqueira et al., (2000) investigated concentric knee extensor and flexor strength in the dominant and non-dominant legs of 3 groups: non-athletes, jumpers (long and triple), and runners/sprinters. After testing subjects on the Cybex 6000 at 60°/s and 240°/s the following points were made: in non-athletes at 60°/s, dominant leg flexors were significantly stronger than the non-dominant flexors; although, dominant leg extensor strength was higher, the difference was not statistically significant; in jumpers and runners at 240°/s, non-dominant leg extensors were significantly stronger than dominant leg extensors. Costain and Williams (1984) studied knee extensor and flexor strength concentrically in teenage female soccer players. Results revealed no significant differences in the legs after being tested on the Cybex II dynamometer at 30 and 180°/s.

Unfortunately, conflicting results in the literature were clearly noticed regarding the differences in bilateral strength production between the lower limbs of soccer players. The reason behind such diversity in the results was due to the differences in the methodological approaches as no two studies had the same exact research model (see Section 2.7 for further critique of this dilemma).

2.3.3 Flexibility

Several studies have examined BA and ROM differences between sides. A study by Boone and Azen (1979) measured active ROM in 109 male subjects, aged 18 to 54 years. Significant BA was found in only a few motions, primarily in the shoulder and elbow, suggesting that asymmetric ROM does occur in the human body. Another study by Macedo and Magee (2008) involving 90 women, aged 18 to 59 years, measured both active and passive ROM, and found significant differences between dominant and non-dominant sides for 34 of the 60 ROMs measured. However, Roaas and Andersson (1982), Agre and Baxter (1987) and Stephanyshyn and Engsbergy (1994), found no significant differences between right and left sides when measuring different joints of the lower limbs. At present the available literature is contradictory and confusing. Two studies (Theoharopoulos et al., 2000; Harvey, 1998) that have researched contralateral flexibility asymmetry have largely looked into its relationship with injury (see Section 2.4.2).

To the researchers' knowledge, there has not been any study that examined differences in flexibility between lower limbs and evaluating an absolute mean difference in asymmetry. Certainly, no study has evaluated the influence of the flexibility in the lower limbs with CMJ.

2.3.4 Effects of injury

BA can be developed as a consequence of injury and the effects of an injury on symmetry could also persists even after following a recovery programme (Yamamoto, 1993; Orchard et al., 1997). Brughelli et al., (2010) investigated BA in kinetic and kinematic variables during running in Australian rules soccer players with previous hamstring injuries. When subjects with previous hamstring injury were compared with non-injured athletes, the results showed the subjects with previous hamstring injury had a leg deficit of 45.9% in horizontal mean force while the non-injured athletes showed a deficit of only 5%. It is clear to see that injuries would cause greater strength imbalances on athletes' performance. However, leg deficits were not measured before the actual hamstring injury occurred and, therefore, it is impossible to determine if the strength imbalance is a result of hamstring injury or whether the strength imbalance is the cause of the hamstring injury. Impellizzeri et al., (2007) has used the ground reaction force and isokinetic/isometric testing to investigate the effect of performance on injured athletes after having an ACL reconstruction surgeries and, found significant correlations between the vertical jumps test with both isometric leg press test and isokinetic leg extension. Furthermore, Schmitt et al., (2015) has also investigated the relationship between performance and readiness to compete in sport after ACL reconstruction surgeries by referring to the quadriceps index (QI = [involved strength/uninvolved strength]*100%). The strength asymmetry guideline presented by Schmitt could provide a safe practice to postoperative athletes since it can identify unstable movements in the affected limb. In summary, the association between bilateral asymmetry and effect of injury remains in conclusive and prospective studies regarding this topic would provide a great understanding in how certain criteria may affect athletes' performance.

2.3.5 Sport specific demands

Asymmetrical movement patterns can be found in many different sports. It is possible that emphasis on one side of the lower body during sport skills (i.e., kicking, use of the drive leg in cricket batting, long-jump), can lead to bilateral asymmetry (Newton et al, 2006). This dominance on one side of the body can lead to imbalances in the overall physical structure, which then leads to asymmetrical structural patterns of flexibility, strength and balance on one side of the body. The "Overload Principle" suggests the occurrence of physical changes in tissue if the stresses imposed are greater than what the tissue is accustomed too, explaining the physical adaptations raising in the overly used limb (Hellebrandt and Houtz, 1956). In some sports BA may be advantageous to achieve the specific movements required by the athlete for the discipline (Gstottner et al., 2009). Strength asymmetries between the lower limbs have been reported in sports with asymmetric kinetic patterns like soccer (Dauty et al., 2003; Arnason et al., 2008). Particularly, in soccer, players are forced to use their lower limbs unilaterally in almost all kicking and cutting skills (Reilly, 2003) and this has been found to alter the strength balance between the two extremities (Fousekis et al., 2009).

2.4 Presence of Asymmetry

Regardless of how BA develops, the fact that asymmetries exist has been evidenced in a variety of tasks. Also apparent is the fact that asymmetries may then affect athletic performance, as well as potentially increase injury risk. Various studies have investigated the factors which affect BA, but the final results have been conflicting. Considering the lower limbs involvement in cyclic rhythmic movements such as walking, running and cycling, studies that investigate BA, reported bilateral asymmetries for the vertical ground reaction force (vGRF) that may vary from 35% to 45% between the lower limbs (Herzog et al., 1989; Chavet et al., 1997; Maupas et al., 2002). Functional asymmetries have been documented in sit-to-stand (Lundin et al., 1995), lifting a box (McMullin et al., 1995), drop landing (Schot et al., 1994), walking (Herzog et al., 1989), and running tasks (Vagenas and Hoshizaki, 1992), supporting the hypothesis that healthy subjects are predisposed to asymmetries during seemingly symmetric tasks.

2.4.1 Effect on Performance

Physical performance has been positively associated with symmetry such that those who are symmetric exhibited more identical physical performance when crossing to either direction during running (Young et al., 2002). However, Cronin and Sleivert (2005) have concluded in their review that, power is not the only criterion that predict the progression of performance in athletes. Thereby, Athletes may fall short of their potential performance due to bilateral asymmetry (Manning and Pickup, 1998; Maly et al., 2010). These physical asymmetries could mean that more work is delivered by one side of the body. For example, a case study exploring leg-length on oxygen consumption reported a substantial effect at a constant workload with varying LLD (Delacerda and McCrory, 1981). It has been found that asymmetries also have an effect upon technique and overall body posture. Additionally, strength asymmetry could possibly affect an athlete's performance by limiting an athlete to favouring the stronger or more dominant side (Yamamoto, 1993; Orchard et al., 1997; Croisier et al., 2002; Askling et al., 2003; Newton et al., 2006). The ability to use both sides of the body equally during such sport could enhance skills and techniques; therefore, it was essential to assess and identify BA in performance.

2.4.2 Increased injury risk

BA is often regarded as a factor that is associated with a greater risk of injury (Klein, 1970; Knapik et al., 1991; Yamamoto, 1993; Orchard et al., 1997; Arendt and Griffin, 2000; Hewett et al., 2001; Soderman et al., 2001; Tyler et al., 2001; Croisier et al., 2002; Newton et al. 2006; Paterno et al., 2007; Fousekis et al., 2010). These studies have concluded, it would be better to avoid BA as much as possible. However, there were studies indicated that there was no relationship between lower limbs asymmetry and injury (Grace et al., 1984; Bennell et al., 1998; Theoharopoulos et al., 2000; Drid et al., 2009).

An asymmetry is thought to place additional strain on the weaker leg, whereby the body has to compensate for increased loading through a joint or limb. Bilateral strength asymmetry has been suggested as a risk factor for ACL injury in female athletes (Hewett et al., 1996, Myer et al., 2004; Negrete et al., 2007; Brophy et al., 2010). Faude et al., (2005) revealed that 80% of the reported incidences in the German women's soccer league were in the lower limbs and, there is a trend toward them tearing their left ACL more often than their right side (non-contact injury). It is thought that the non-dominant leg may be more susceptible to ACL injury because of less effective dynamic restraints. Interestingly, Knapik et al., (1991) found that strains and sprains were more likely to occur on the left leg, which was determined to be the weaker side. However, Bahr and Krosshaug (2005) suggested that in certain sports, the dominant leg may be at increased risk of injury because it is preferentially used for kicking, pushing off, jumping, or landing.

The literature had a contradicted view about the relationship between ROM and lower limb injury. A number of authors have found a predisposition to injury in athletes with reduced flexibility (Liemohn, 1978; Ekstrand & Gillquist, 1983; Knapik et al., 1991; van Mechelen et al., 1992; Worrell, 1994; Garrett, 1996; Lambson et al., 1996; Rahnama et al., 2005). Conversely, Orchard et al. (1997), Hennessey & Watson (1993) and Arnason et al., (1996) found no correlation between ROM and muscle injury. It is believed that lack of flexibility may produce early muscle fatigue or alter the normal biomechanics of movement, predisposing injury, especially putting hamstrings and quadriceps muscles at risk (Liemohn, 1978; Ekstrand & Gillquist, 1983; Knapik et al., 1991; Worrell, 1994; Soderman et al., 2001; Witvrouw et al., 2003). It is believed that around 17% of injuries in soccer has been attributed to muscle tightness (Ekstrand and Gillquist, 1983). However, scientific evidence on this issue is equivocal and some authors have hypothesised that there simply is a natural difference between sides (Gunal et al., 1996; Barnes et al., 2001).

Consequently, the link between BA and injury remains speculative. The contradiction in results may be attributed to research designs using various methods of measuring muscle tightness, diverse injury types, and a variety of sports with different inherent risks. Therefore, establishing an objective measurement in the form of standardising norms for key criteria in lower limbs would aid in exploring how disadvantageous in sport to perform asymmetrically during a competitive season. Hence, objective measurements tend to be utilised often by clinicians to diagnose any complications in athletes' performance or to stand on their readiness to compete again.

2.5 How much asymmetry between limbs is significant

The topic of BA gives rise to the questions, what is a critical value of asymmetry between lower limbs. As well as, what are the critical values that associated with significantly increased risk of injury. However, in spite of abundant literature dedicated to the topic of bilateral asymmetry, clinical cut-off points for bilateral asymmetry remain inconclusive (Mendiguchia et al., 2012). There was no consensus in the literature about what percentage of asymmetry difference between lower limbs BA gives rise to an increased injury risk or reduction in performance. Values ranged from 10% (Burkett, 1970; Dauty et al., 2003; Schiltz et al., 2009), 15% (Baumhauer et al., 1995; Bennell et al., 1998; Croisier et al., 2002) and 20% (Fowler and Reilly, 1993; Croisier et al., 2002; Myer et al., 2004) for isokinetic strength testing. For functional hop or jump tests and flexibility a value of 15% has been postulated as clinically significant (Barber et al., 1990; Knapik et al., 1991; Noyes et al., 1991; Barber et al., 1992; Wilk et al., 1994; Petsching et al., 1998; Fitzgerald et al., 2001; Croisier et al., 2003; Impellizzeri et al., 2007). However, Daly and Cavanagh, (1976) and Herzog et al., (1989) used any deviation from 50-50. Much of the research has focused on the increased risk of hamstring injuries, it is thought a 10% (Burkett, 1970; Pollard and Quodling, 1999; Dauty et al., 2003) to 15% (Knapik et al., 1991; Bennell et al., 1998) increases hamstring injury risk. Such percentage (10-15%) tends to be addressed across most of the attributes as the cut-off percentage for asymmetry.

Petsching et al., (1998), Croisier et al., (2002) and Newton et al., (2006) have highlighted the relationship between the balance of strength values between a dominant and non-dominant leg and categorised a percentage of their subjects to have imbalances based on a cut-off point of 15%. However, if the cut-off point had been set to 10% as used in other similar studies the results may have classified fewer subjects as being diagnosed with BA. Conversely, Yoskioka et al., (2010) used a 10% cut-off; this may have underestimated the number of subjects with asymmetry. Such differences in the cut-off percentages raised more questions whether more research is needed to clinically diagnose asymmetry for all attributes using an absolute difference between limbs.

A major problem when trying to draw conclusions across asymmetry studies is the fact that some researchers have looked at the asymmetry between left and right, whilst some have evaluated difference between dominant and non-dominant. Section (2.3) discussed the problems this produces, making it difficult to draw conclusions. Furthermore, there are many methodological flaws in these studies as detailed in Section (2.7). Therefore, comparisons between studies are difficult.

To summarise, BA is thought to increase the risk of injury and possibly affect athletic performance (Orchard et al., 1997; Croisier et al., 2002). However, the threshold at which a deficit becomes problematic is the subject of conjecture. There is no consensus about what should be measured to constitute BA and it is unclear as to how threshold values such as 15% are derived and whether all injuries have the same threshold. Previous researches into asymmetry have not identified definitive cut-off percentages or what is a “typical” or “safe” difference between lower limbs, thus it is still unknown as to what is classified as asymmetry. For that, it was imperative to establish such cut-offs in order to clinically diagnose BA.

2.6 Relationship between tests evaluating asymmetry

Newton et al., (2006) found that asymmetry in the peak and averaged vGRF during the CMJ did not relate to any of the other strength measures. Conversely, Impellizzeri et al., (2007) showed that while vGRF asymmetry of the CMJ did not correlate with asymmetry in the unilateral isokinetic knee extension strength, it correlated significantly with force asymmetry during a maximum effort squat. Menzel et al., (2013) has also stated that countermovement jumps as well as isokinetic testing were useful and reliable tests that diagnose asymmetry in lower limbs. They attributed these differences to the fact that the CMJ requires a well-coordinated interaction of all lower limb joints, while the isokinetic knee extension is only indicative of knee extensor strength. Impellizzeri et al., (2007) concluded that the CMJ test might be a more functional way to assess BA. However, because the strength of each limb was not measured independently, the relationship between strength asymmetry and asymmetry in force production during a CMJ could not be verified. The lack of statistical significance found by Newton et al., (2006) may be related to the fact that his study has a small sample size (n=14). Impellizeri et al., (2007) concluded that OKC, isokinetic tests should be used when the purpose of the assessment is to quantify bilateral strength asymmetry of specific lower limb muscles such as the knee extensors and flexors. However, the CMJ and other CKC tests provide a global measure of bilateral strength asymmetry, because these require the coordinated action of many lower limb muscles.

Therefore, CMJ may be more functionally relevant to daily life and sport activities. Furthermore, the predictability of jump performance based on a measure of isokinetic torque development of a single muscle group may be poor because jumping requires the use of various muscle groups, and more complex coordination; hence, isokinetic testing may not be movement specific enough to predict jump height (Baker et al., 2001; Ugarkovic et al., 2002).

Conflicting views exist whether NFPT scores reflect lower limb muscular strength. Several authors have concluded a positive correlation between NFPTs and isokinetic testing (Barber et al., 1990; Noyes et al., 1991; Barber et al., 1992; Wilk et al., 1994; Wilson and Murphy, 1995; Petschnig et al., 1998; Augustsson and Thomee, 2000; Ross et al., 2002; Tsiokanos et al., 2002; Keays et al., 2003; Hewit et al., 2012). Some authors have indicated a moderate correlation (Greenberger and Paterno, 1995;

Tomioka et al., 2001) whereas other researchers, have reported minimal or no correlation (Anderson et al., 1991; Swarup et al., 1992; Ostenberg et al., 1998; Kovaleski et al., 2001). The discrepancies in results may be derived from differences in methodology, subject populations, testing methods, equipment, and pathological conditions.

While the literature suggests that 1LH may confirm functional limitations, their ability to identify specific deficiencies is unclear (Barber et al., 1990; Noyes et al., 1991). Whether poor performance on a 1LH is simply due to lower limb-strength deficits or by inadequate balance or power remains to be determined. To the researchers' knowledge, there are no studies that have examined the relationship between the CMJ and NFPT or CMJ with 1LCMJ.

2.7 Criticism of other asymmetry studies

As with any research, findings are somewhat dependent upon the way data was collected and analysed. This is especially true when attempting to review BA literature, which lacks consistency. This is largely due to differences in the methodologies used, whether researchers have studied the dominant/non-dominant, preferred/non-preferred, right/left, or strongest/ weakest limbs, and how researchers have defined dominant or preferred leg.

One of the major criticisms found in this literature review was, as many researchers have performed their statistical analyses differently in their studies. For example, a number of studies have compared their selected criteria after calculating the mean difference between lower limbs using t-test and one-way ANOVA test (Hvid et al., 1981; Beckett et al., 1992; Astrom and Arvidson, 1995; Sobel et al., 1999; Newton et al., 2006). Because these analyses often find no statistical differences between the lower limbs in a sample, it may be assumed that both sides are symmetrical. However, these analyses were only sensitive to systematic differences in mean values between lower limbs and, they do not allow quantifying the range and magnitude of left-right differences measured within each subject. A the few studies have reported mean left-right differences within subjects and, substantial asymmetries have been noted (Livingston and Mandigo, 1997; Rahnama et al., 2005). Furthermore, when performance measures were collected and pooled prior to bilateral comparisons, it was nearly always concluded that lower limb function was bilaterally symmetrical. This held for simple left/right and also dominant/non-dominant comparisons (Goslin and Charteris, 1979; Holmes and Alderink, 1984; Berg et al., 1985). When analyses were conducted using a single-subject design or a case study basis, where BA was quantified for each subject prior to pooling data, asymmetries were regularly identified (Singh, 1970; Daly and Cavanagh, 1976; Arsenault et al., 1986; Vagenas and Hoshizaki, 1986). It was likely that, despite many subjects being right-sided, some subjects maybe left-legged dominant and that would, nullifying strength differences when averaged across groups. Consequently, even if a number of subjects were quite asymmetric in the way they performed the required tasks. This would be masked by the process of pooling data from all subjects where perhaps the values that represent the right-biased performance were negated by the left-biased performance.

Another problem was that throughout the literature a popular way to quantify BA, was by the use of indices. For example, Daly and Cavanagh (1976) used an Index of Asymmetry (IA) to compare differences in the work output between the dominant and non-dominant lower limbs, while pedalling on a bicycle ergometer at different speeds and resistance settings. Their IA was calculated as follow:

$$\mathrm{IA} = \frac{\text{Dominant}}{\text{Non-dominant}} \times 100$$

With this method, BA is represented by IA deviating in either direction away from 100. This example demonstrates the problem associated with this. If the dominant leg generated a force of 1200N and the non-dominant leg generated 800N, the IA score would be 150%. However, if the forces were reversed, with the non-dominant leg generating 1200N and the dominant leg generating 800N, the IA score would be 66.7%. Hence, a different index value would be obtained for the same level of asymmetry. The numerous indices that have been used previously to quantify asymmetry have made it difficult to interpret and compare results from different studies.

Furthermore, no two studies had identical protocols. Differences in subjects (non-athletes, athletes, variety of sports), inclusion/exclusion criteria, sample sizes or methods (muscles tested (flexors, extensors or both), muscle action (concentric, eccentric, or both), testing speed (ranged from 30 to 300°/s), warm-up protocol, familiarisation methods, test repetitions, order of testing, rest periods, variable measured and equipment used. Such variance between studies may have attributed to conflicting results (Newton et al., 2006; Theoharopoulos et al., 2000; Rahnama et al., 2005; Croisier et al., 2006). These inconsistent study designs, in particular the different techniques used to quantify BA, can lead to conflicting interpretation of results. Therefore, comparisons between studies cannot be made with confidence and conclusions cannot be postulated. With such contradictions in the literature of the sources of BA, presence of BA, relationship of BA and increased injury risk, ways of measuring BA and the relationship between the various procedures as well as the problems and criticisms identified with asymmetry literature, suggests that further and more comprehensive research is needed to fill those gaps.

In conclusion, the literature review has highlighted the main areas based on the discussions and recommendations reported by previous researchers in the field of BA. As it firstly, enclosed a number of key criteria that been utilised in previous studies then, categorised them based on function in a diagram (Figure 2.1). The use of these criteria during investigations were either to aid in enhancing performance in bilateral tasks or may assist in identifying abnormalities in movement that could cause uneven loadings which might be utilised as a predicting measure of injury. Secondly, it has addressed the controversy of defining BA in lower limbs and how researchers have sat their methodologies along with their rationales. Thirdly, it has revealed a number of different scope of interests of the researchers when examining BA, as no two studies were found in the literature review that have the same model of testing. Lastly, it has demonstrated a diverse statistical analysis approaches in how to diagnose BA. Such controversy in examining BA made it really hard to standardise a useful protocol which can be utilised as an assessment tool by rehabilitation teams to diagnose athletes for different purposes. Therefore, this thesis has intended to tackle the aforementioned gaps in literature by establishing a novel methodology in defining, diagnosing and setting norms of key criteria in lower limbs for BA. Such approach, has a great potential to allowed the rehabilitation sport teams to screen their athletes objectively and more comprehensively using the proposed model in the next chapter.

3.0 RESEARCH MODEL

The research model of this thesis was formulated firstly and foremost in order to establish normative data of bilateral asymmetry for key criteria in lower limbs. The procedure of collecting the key criteria was presented in Section 3.3. This thesis has presented a novel statistical analysis approach to diagnose BA and was illustrated in section 3.3.1. The criteria were specifically chosen based on previous researches done in the field of BA in lower limbs and, no specific order was set to perform the bilateral asymmetry analysis bundle (BAAB) for the athletes. Moreover, the outcomes from the BAAB was sub-categorised based on the level of athletes. Thereby, norms generated in study one (Chapter 4) were related to sub-elite athletes whereas the norms found in study two (Chapter 5) has represented the cut-offs of the elite ones. Furthermore, as shown previously in the literature review (Section 2.6), researchers tended to investigate a selection of few criteria in their analyses whereas; this research has a wide range of variables that been collected in order to examine the relationships between on criterion to another utilising a larger sample size when compared with the previous studies (Chapter 6). Lastly, the necessity for a test that simulates an actual performance of athletes which may provoke certain level of BA in the lower limbs has raised a number of hypotheses. Therefore, the last study has investigated the relationship between two functional performances (running and CMJ) and, the running gait protocol was described in (Chapter 7).

3.1 Ethics

Ethical Approval number HSCR12/07 was granted from the Research, Innovation and Academic Engagement Ethical committee panel of University of Salford (Appendix A).

3.2 Consent

All subjects were provided with an information sheet of the purpose of the study (Appendix C) before testing and were asked to complete a consent form (Appendix B1) or (Appendix B2) prior to their participation. Subjects were questioned about their injury history and participation in sport (Appendix D) along with obtaining general information (age, height, mass, gender, etc.). the inclusion criteria included; not having a surgical intervention in the last year on their lower limbs, not having serious injuries that prevented athletes from not participating in sport in the last six months, not having medical complications at the day of testing (such as flu) that might affect their maximum performance and all participants were informed not to have a vigorous exercise the day before the testing day.

3.3 Procedures

Subjects have completed the whole bilateral asymmetry analysis bundle in the same day. Subjects were instructed to wear suitable athletic clothing and footwear.

The order of these tests was randomised to reduce testing effects and the order for either limb was counterbalanced for all tests to reduce order bias. All subjects were familiarised with the procedures prior to testing. Subjects rested for a minimum of five minutes between tests. All equipment utilised was calibrated according to the manufacturers' standardised procedures. All measurements on one test station were made by the same examiner for all subjects, which, according to Norkin and White (2009), gives a higher reliability compared to if the measurements had been taken by different examiners. Reliability data for all tested variables will be presented later in study one. Lastly, all measurements were recorded for both lower limbs.

3.3.1 Data Processing and Statistical Analyses

All data was initially analysed using Microsoft Excel (Microsoft Corp., Redmond, USA). The mean and the standard deviation (SD) were calculated for all variables being tested.

BA was expressed as a percentage and was calculated by dividing the difference of both legs over the maximum score of either right or left leg score (Equation 1).

$$AAV\ \% = Abs\left[\frac{(right\ leg\ score\ -\ left\ leg\ score)}{(Max.score\ of\ either\ right\ or\ left\ leg\ scores)}\right]x100$$

[*Equation 1*]

A positive value indicated that the right leg was stronger while a negative value indicated the left leg was stronger. To identify whether an asymmetry existed, the average of the absolute difference ± *SD* between the right and left limb was determined. Asymmetry was then "diagnosed" by calculating the sum of AAV and SD (Equation 2) of each criterion and, the total represented "threshold percentage" of that particular criterion.

$$Threshold\ \% = Avg.\ AAV + SD \qquad [Equation\ 2]$$

Since the asymmetry agreement percentage is a novel approach to examine the relationship between two variables, no exact percentages of to which extend an agreement can be considered as being meaningful or not. For example, when researchers in the sport rehabilitation field examine the ICC in their reliability studies, a scale of grading between poor to excellent was given based on the produced percentage of each test. Thus, assuming normal distribution of the asymmetry, then it would be expected that 68.2% of the population would fall within 1SD (balanced population) of the mean, with 31.8% of the population may exhibiting an asymmetry. Based on this assumption, this would help establishing a meaningful grading scale to evaluate the agreement between to variables. Therefore, to explore the association in diagnoses of asymmetry between variables a qualitative measurement of "agreement" was used based on the absolute mean difference criteria [Equation 3]. This required, for example, if the diagnosis between variables was the same, i.e. (balanced=balanced; right=right, left=left) then this was given a value of 1. For contrasting diagnoses, a value of zero was given. The percentage "agreement" was then determined by the sum of all the individual agreements expressed as a percentage of the number of subjects.

$$Asymmetry\ Agreement\ (\%) = \left[\frac{frequency\ of\ like\ for\ like\ diagnoses\ (asymmetrical\ \&\ balanced)}{no.\ of\ subjects}\right] x100$$

[*Equation 3*]

Since this is a novel approach to evaluating the association between factors the following interpretation will be adopted:

66.5% and below= No association (for every one agreement there is one disagreement)
66.6% and above= Low association (two out of 3 comparisons are in agreement)
75% and above= Medium association (3 out of 4 comparisons are in agreement)
80% and above= High association (4 out of 5 comparisons are in agreement)

This interpretation will be used when examining the association between variables that may be related to bilateral asymmetry.

3.3.2 Warm Up

Subjects were allowed to do a self-selected warm up before testing. However, no static stretching was allowed, since previous studies have demonstrated negative effects of stretching on various jump variables (Cornwell et al., 2001).

3.3.3 Anthropometric Measurements

Height (cm) was measured using a free standing stadiometer, measuring to the nearest 0.5cm. The body mass (kg) was measured using scales measuring to the nearest 0.5kg. To assess leg length, the subjects were instructed to position themselves supine on a plinth and, a tape measure was used to measure the distance in centimetres (cm) between the anterior superior iliac spine (ASIS) and the medial malleolus (Figure 3.1). Woerman and Binder-Macleod (1984), found that the measurement from the ASIS to the medial malleolus was the most accurate and precise clinical technique when compared with mini scanogram.

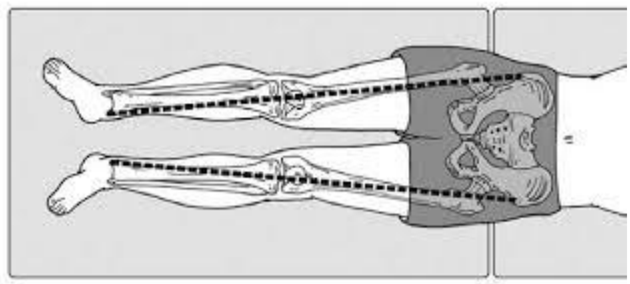

Figure 3.1: Leg length measurement, from ASIS to medial malleolus (Bradley, D. 2011)

A tape measure was used for measuring thigh circumference detailed by Norkin and White (2009). Subjects were positioned supine on a plinth and asked to passively flex the knee while the inguinal crease and the proximal border of the patella were marked (Figure 3.2). The point of measurement was then marked and recorded at exact point halfway between the two marks. Lastly, for the measurement of calf circumflex, subjects were asked to be in fully supine position as before with the knee was not flexed as before. To find the point of measurement, the tape measure was wrapped horizontally around the entire calf and moved up and down until the maximum circumference was found (Figure 3.3).

Figure 3.2: Thigh circumflex measurement

Figure 3.3: Calf circumflex measurement

3.3.4 CMJ

Countermovement jumps were performed as a closed kinetic chain test to measure the bilateral asymmetry muscle force outputs of the lower limbs. The test of the two-legged countermovement jump measuring vGRF were made using two adjacent force platforms. As testing took place in different places two different dual force platform systems were used, Kistler 9286AA portable force platforms (Kistler Group, Winterthur, Switzerland) and PASCO portable force platforms (PASCO Scientific, Roseville, USA). As the study was examining differences between left and right forces as opposed to absolute forces per se then this was not an issue.

Prior to testing, the force plates were recalibrated for each participant before performed their jumps and were checked for the consistency of the force measurement. This was accomplished by requesting each subject to stand still on each plate to ensure that they have the same body mass within a difference of 10N between both force plates (Figure 3.4).

Subjects performed a series of CMJs standing with one foot in the centre of each force-plate involving body weight (BW) only. Subjects were instructed to perform a CMJ for maximum height and effort using a self-selected countermovement depth. In order to restrict arm movements, subjects completed the BW jump trial while holding in both hands a wooden stick across their shoulders for a better control (Figure 3.5).

In total, maximal jumps were performed. Three CMJs were performed. Three 1LCMJs were performed on each leg to enable comparison of unilateral and bilateral tests of asymmetry (Figure 3.6). Thirty seconds was the time interval to complete the three jumps in both CMJ and 1LCMJ. Between sets, the rest period allowed was one minute. VGRF data were collected using a sampling rate of 1000 Hz. For the Kistler system data was collected through Bioware software v5.1.1.0 from Kistler's group and, as for the PASCO system, DataStudio software v3.0 was utilised. All data were processed using a custom-designed Force Analysis Program (Apache.org v2.0) and this calculated a number of performance and asymmetry measures (Figure 3.4). From the total force (summation of left and right forces) it was possible to determine the maximum displacement of the centre of mass (double integration of the acceleration data) and this served to differentiate between eccentric and concentric phases. Asymmetry evaluation was based on three measures; Peak forces, average eccentric force and average concentric force. Lastly, mimicking previous researchers (Newton et al., 2006; Impellizzeri et al., 2007), the mean and standard deviation of three trails were extracted for each criterion for analysis.

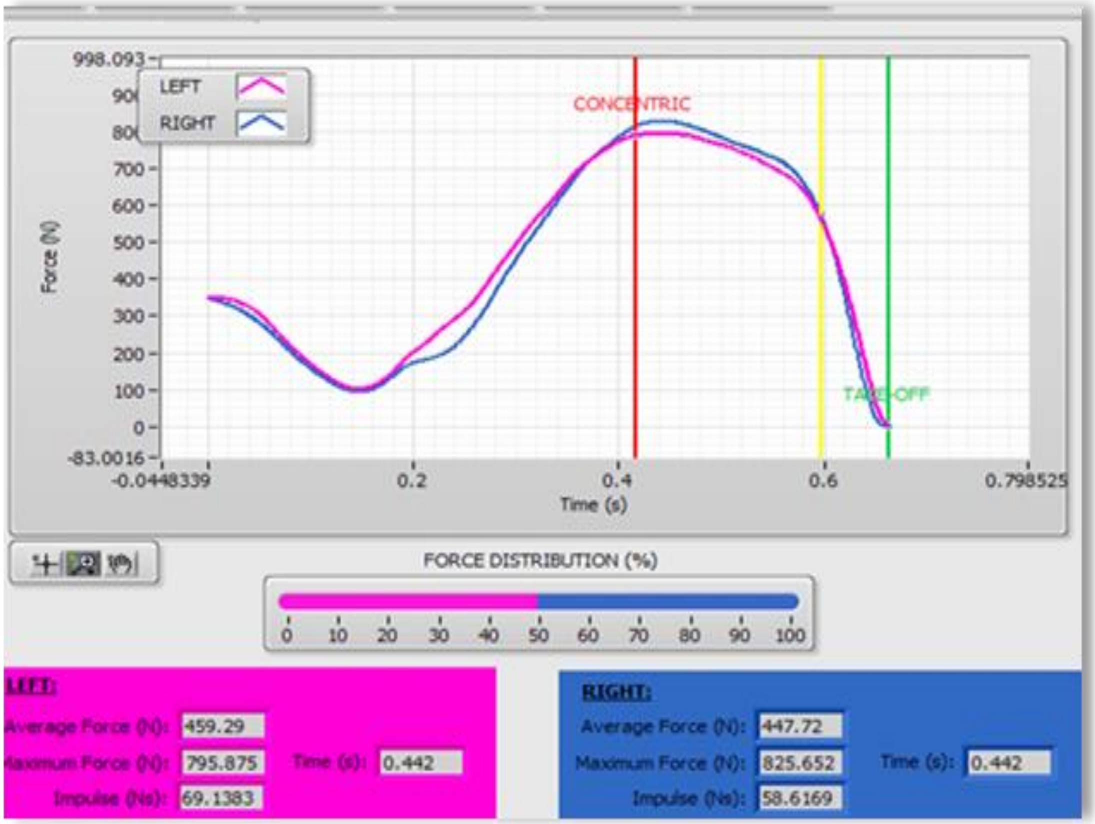

Figure 3.4: Force platform profile

Figure 3.5: Subject performing CMJ

Figure 3.6: Subject performing 1LCMJ

3.3.5 Flexibility

Muscle length was assessed in quadriceps, hamstrings and gastrocnemius-soleus (ankle joint ROM) using physical examination techniques as described by Norkin and White (2009). Range of motion was evaluated under the assumption that joints motion were limited by tightness of these muscles. The quadriceps muscle was tested using the modified Thomas test (MTT). Subjects were asked to sit at the end of a plinth, roll backwards and pull one knee towards the chest while the leg being measured hung off the end of the plinth for three times as prescribed by Harvey (1998). A Casio EXF1 video camera sampling at 30 Hz recorded this position for both legs. The images of the subjects were uploaded to a video software (Quintic Biomechanics 9.03v17, Quintic Consultancy Ltd., UK) for analyses and, the angles generated from the lines passing the marked landmarks between the lateral malleolus, head of fibula and the greater trochanter were measured (Φ) from the sagittal plane (Figure 3.7).

Figure 3.7: Subject performing MTT and the Φ angle was taken for analysis (image as shown by Quintic Biomechanics software)

The hamstring muscle was tested using the active knee extension (AKE) test. Subjects were positioned supine on the plinth with the hip stabilised at 90° flexion and, the thigh was positioned parallel to the vertical arm of a wooden measuring frame. The knee was relaxed in a flexed position. From this position, subjects were required to actively extend the knee maximally, while maintaining the anterior part of the thigh in contact with wooden frame and, keeping the hip in contact with the plinth. A Casio EXF1 video camera sampling at 30 Hz was used for recording the movement from the sagittal plane. The image of the subject was uploaded to the video analysis software. By default, Quintic Biomechanics generated a vertical line that creates an angle when drawing a line that passes through marked landmarks (lateral malleolus and head of fibula). A vertical wooden arm frame was utilised as a reference point of maximal knee extension; the angle (Φ) around the knee was taken for measured. The mean of the three trials were taken forward for analysis. A value of 0° corresponded with a full leg extension (Figure 3.8).

Figure 3.8: Subject performing AKE and the Φ angle was taken for analysis (image as shown by Quintic Biomechanics software)

Lastly, the gastrocnemius-soleus/ankle's dorsiflexion (DF) ROM was measured from lunging position (with weight-bearing) using a universal goniometer. The researcher marked the fibular head as well as the base of the 5th metatarsal as stated by Bohannon et al., (1989). The starting point of the test began from keeping subjects at fully standing position then, placing the pivot point of the goniometer directly over the lateral malleolus with one arm pointing towards and crossing the 5th metatarsal while, the other pointing toward the fibular head (Figure 3.9). After that, subjects were asked to lunge (knee flexed) as far as they could while maintaining the heel in contact with floor and, difference between the acute angles from the starting point till the end one represents the flexibility of ankle DF. Three measurements were taking for analysis.

Figure 3.9: Ankle dorsiflexion measurement

3.3.6 Isokinetic strength testing

Concentric peak torque of right and left knees' flexors and extensors muscle groups were tested for strength. Tests were executed at a constant speed at 60°/s using isokinetic dynamometer (Kin Com). This speed was chosen to represent the strength measurements of isokinetic testing as it represents the most appropriate speed to evaluate the strength of knee flexion and extension muscles group at the concentric phase (Dvir, 2004). Reliability of the Kin Com isokinetic dynamometer at 60°/s has been established previously by Graham-Smith et al., (2013) and, the results from the within-session intra-class correlation coefficients (ICC) were for knee's extension and flexion PT (concentric phase) = 0.93 and 0.95 respectively. Subjects were positioned according to the Kin Com's manual (Figure 2.1) thus, they were seated with the hip joint at 90° (supine position = 0°). The centre of rotation of the knee was aligned with the dynamometer arm rotation axis while extraneous movement was prevented by body straps, positioned at the hip, shoulders and tested thigh. The resistance pad attached to the lever arm was secured around the distal tibia. Subjects were asked to hold onto the side handle grips during familiarisation and testing. After that, the measurement of moment for the leg was gravity corrected at 30° of knee flexion (Reilly, 2003). Subjects were allowed to perform a self-selected amount of repetitions at 60°/s for familiarisation. Peak torque (PT) was taken from 0 to 90° of knee flexion (full extension = 0°). As a consequence of the variance in literature about the repetition of trials in each set (3-6 repetitions), it was decided to instruct the subjects to perform five repetitions of maximal knee flexion and extension concentrically at 60°/s (theoharopoulos et al., 2000; Newton et al., 2006; Croisier et al., 2008). The starting leg (left or right) was randomly selected to avoid any order effect on data and minimise the effects of learning bias. Following the testing of one leg and, there was a minimum of two-minute rest period before testing the other leg as recommended by previous researchers (Hislop et al., 1967; Heinrichs et al., 1995). Verbal instructions and visual feedback was standardised. The isokinetic test data results were exported from the system in ASCII format and uploaded in excel sheets from Microsoft for further analyses. Torque – angle profiles were inspected to ensure that the peak torques occurred within the isokinetic range. Five repetitions were performed for each test and the highest peak torque was used to quantify asymmetry.

3.3.7 Neuromuscular Functional Performance Tests

The one-legged hop (1LH) for distance was performed in accordance with the descriptions by Daniel et al., (1988) and Barber et al., (1990). The test required the subjects to hop from and land on the same leg, and hold the landing position for 2 seconds; otherwise the jump was deemed invalid. Subjects were instructed to jump for maximum distance and the distance between the toes at the zero mark to the heel at landing was measured (Figure 3.10). Three measurements were taken on each leg and the mean was taken forward for asymmetry analysis. The first leg to be tested was chosen randomly.

Figure 3.10: One-legged hop (1LH)

The one-legged triple hop (1LTH) was performed as described by Noyes et al., (1991). The test required the subjects to jump three consecutive maximal hops forwards and land on the same tested leg each time (Figure 3.11). The 1LTH was measured in total distance from the start line to the point of heel contact after the third consecutive hop. Three measurements were taken on each leg and the mean was taken forward for asymmetry analysis. The first leg to be tested was randomly chosen.

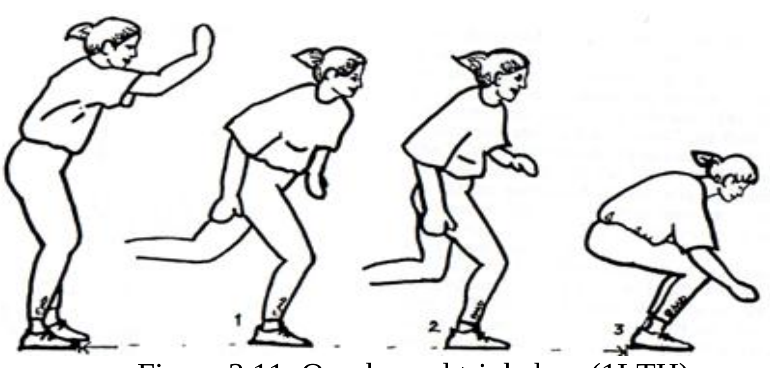

Figure 3.11: One-legged triple hop (1LTH)

4.0 STUDY ONE

Title: Reliability of measures used to assess and diagnose lower limb asymmetry.

4.1 Introduction

The topic of bilateral asymmetry in lower limbs gives rise to the question, what is a critical value (threshold) that can be used to diagnose asymmetries in performance that warranted intervention (Section 2.5). Despite how bilateral asymmetry developed, many researchers have utilised a variety of criteria in lower limbs to investigate whether asymmetries could impact performance (Masuda et al., 2003; Rahnama et al., 2005; Newton et al., 2006; Gioftsidou et al., 2008). Asymmetry was evaluated often to examine strength and flexibility (Goslin and Charteris, 1979; Holmes and Alderink, 1984; Berg et al., 1985; Knapik et al., 1991; Orchard et al., 1997; Croisier et al., 2002; Rahnama et al., 2005; Newton et al., 2006; Impellizzeri et al., 2007), other researchers investigate jumping abilities (Noyes et al., 1991; Newton et al., 2006), power endurance (Valdez et al., 2004), anatomic structure (Singh, 1970), kinematic, kinetic, and muscle activity characteristics (Goslin and Charteris, 1979; Arsenault et al., 1986; Vagenas and Hoshizaki, 1988; Herzog et al., 1989). Moreover, asymmetries in lower limbs may affect athletes' performance (Young et al., 2002), which potentially may or may not lead to injury risk (Section 2.4.2). A number of studies (Grace et al., 1984; Bennell et al., 1998; Theoharopoulos et al., 2000; Drid et al., 2009) have investigated many criteria which affect BA however; the conclusion of such dilemma is still conflicting and inconclusive.

Studies have reported that asymmetries have an effect upon body kinematics and body posture (Yamamoto, 1993; Orchard et al., 1997; Croisier et al., 2002; Askling et al., 2003; Newton et al., 2006). In addition to that, strength asymmetry may affect athlete's performance by limiting the athlete when using the favoured or stronger or more dominant side of his limb. Furthermore, using both lower limbs equally during competition could enhance skills and performance in symmetrical movements; therefore, it is essential to assess and identify BA (Section 2.4.1).

The literature revealed inconsistency about the percentages found for BA in lower limbs as the values ranged from 10–20 % (Section 2.5). Some researchers base their cut-off percentages on an arbitrary value of 15% to categorise their subjects from being balanced or not (Petsching et al., 1998; Croisier et al., 2002; Newton et al., 2006). However, Yoskioka (2010) suggested a cut-off of 10%, such percentage value, may classify fewer subjects from being diagnosed with BA. Instead of the previously introduced percentages, two studies have addressed asymmetry as any deviation from 50-50 scoring methodology (Daly and Cavanagh, 1976 and Herzog et al., 1989). Such differences prove more research is needed to clinically diagnose each criterion by it is own for asymmetry. For that, addressing a novel protocol to diagnose bilateral asymmetry between lower limbs could focus the direction of practitioners and researchers into more coherent future studies which follows the same statistical analysis methodology or, by tailoring a similar battery of testing for different criteria or outcomes.

Speculation between bilateral asymmetry and enhancing performance or even predicting injury risk are still inconclusive due to the contradictions in the scope of research interest. Such diversity in research designs, was noticed as a result of various methods of measuring muscle tightness, varied injury types, and a mixture of sports with different inherent risks. BA in lower limbs was proposed as a factor that increases risk of injury and possibly affects athlete's performance (Orchard et al., 1997; Theoharopoulos et al., 2000; Croisier et al., 2002; Newton et al., 2006). Although, the threshold at which asymmetry becomes problematic is still conjecture. There is no agreement about what should be measured to establish BA in lower limbs and yet, it is still unclear as to how threshold values such as 15% are derived and whether all criteria have the same exact threshold percentages. Previous research into asymmetry has not identified a definitive cut-off percentage or what is a "normal" or "absolute" difference between limbs, thus it is still unknown as to what is classified as asymmetry (Section 2.5). For that, it is imperative to establish a protocol that would standardise the current practice in term of clinically diagnose BA criteria in lower limbs and setting definite threshold percentages for each one of them.

Lastly, when investigating bilateral asymmetry during double legged movements such as squats and CMJ's there is no indication as to whether the same level of asymmetry would exist if CMJ was performed with body weight only versus CMJ with additional loads. This has yet to be established in the literature. Given that ‘functional tests’ are becoming increasingly more popular in the clinical world, then it is important to understand the implications of testing with respect to the levels of loading required to establish more reliable assessments of bilateral asymmetry. The purpose of this main study was to examine the reliability of the executed tests which will be used for all the studies in this thesis and, to compare the results with the findings in the literature. Furthermore, an investigation took place to examine the effect of external loading as one of the factors that might affect bilateral asymmetry.

Additionally, an auxiliary study was designed based on a mixed-athletes (elite and sub-elite) group retrospectively, in order to compare their countermovement jump (CMJ) performance on the two-legged CMJ without adding any load to them, two-legged countermovement jump along with additional 20% of body weight in the form of weight bar which been placed across the shoulders (CMJBW+20%) (Figure 4.1) and, two-legged countermovement jump plus additional 40% of body weight (CMJBW+40%), along with anthropometric measurements, isokinetic strength of the quadriceps and hamstrings muscles, range of motions of the quadriceps, hamstrings and ankle joint (dorsiflexion only) and NFPTs. The implication of resisted training technique has been practiced very often by couches and sport and exercise trainers to enhance the performance of the athletes (Petrakos et al., 2016). For the various tests used, the performance of each leg was obtained for subsequent comparison between left and right legs to examine the bilateral asymmetry between lower limbs.

Figure 4.1: Subject performing CMJBW+20%

Therefore, the aims of this study in general were to: quantify the ‘absolute asymmetry value’ as a threshold to diagnose BA across all measures of strength, flexibility, anthropometry and one and two-legged CMJ in a sub-elite population; to quantify the reliability of these measures and; to examine the effect of additional loads of 20 and 40% of BW in the diagnosis of asymmetry in bilateral CMJ’s.

4.2 Methodology

One hundred and thirty-nine injury-free sub-elite athletes (Females= 24, Males= 115) participated in this study. The exclusion criteria for this study and the upcoming ones were, athletes having a surgical procedure in their last year on one or both lower limbs or, having an injury that permitted them from not competing in sport in the last six months or, having medical problems at the day of testing (i.e. flu) that could affect their maximum performance. Moreover, participants were noticed prior to examination for not performing any strong workout the day before their testing day. Nevertheless, to ensure a proper outcomes of the data, the athletes were familiarised with all the tested tasks before undergoing the actual testing procedure. The bilateral asymmetry analysis bundle was prescribed in detail earlier between sections 3.3.2 and 3.3.7. The mean ± SD of athletes’ demography was presented for all participants (Females and Males) in Table 4.1.

Table 4.1: Mean ± SD of sub-elite athletes’ demography (Total n=139; Females= 24 and Males= 115).

Variable	**Age** (years)	**Height** (cm)	**Mass** (Kg)
Females	21.4 ± 5	164.1 ± 5.6	60.5 ± 6.1
Males	22.5 ± 5.2	177.8 ± 7.2	79.5 ± 13.1
Combined	22.3 ± 5.1	175.4 ± 8.7	76 ± 14.2

The sub-elite athletes (not competing professionally in sport) were involved in a range of different sports (i.e., collegiate fencing club) with soccer players being the highest participants in this study (Table 4.2). On the other hand, rowing and cycling showed the least participants. For the sake of accurate grouping, a number of participants were categorised as “gym” as they have described their favourite sport as gym exercises and, same concept was duplicated with "martial arts".

Table 4.2: Number of sub-elite athlete participants within each sport (n=139).

Sport	Number of Subjects
Athletics	5
Cricket	4
Cycling	2
Soccer	53
Gym	32
Martial arts	11
Rowing	3
Rugby	17
Runner	12

The bilateral asymmetry analysis bundle (BAAB) starts after completing the consent form (Section 3.2). The subjects were questioned about any previous serious injuries in the last six months along with some general information (i.e. age, gender, etc.). Subjects were instructed to perform a five minute warm up exercise before starting the test (Section 3.3.2). A randomised order was executed to complete the BAAB (Section 3.3.2 – 3.3.7) and, the stations of the whole examination consisted of the following;

A) Anthropometric Measurements

   Each subject has been measured for mass (kg) and height (cm). Followed by, leg length (cm) and thigh and calf circumflexes (cm) (Section 3.3.3).

B) Counter Movement Jumps Testing

   Subjects were asked to stand on two adjacent force platforms (1cm apart) and performed three two-legged countermovement jumps (CMJ). Followed by, three one-legged countermovement jumps (1LCMJ) on each leg. Athletes were instructed to jump as high as they could (Section 3.3.4).

C) Flexibility Measurements

Three key measurements were performed to the athletes to assess their flexibility of the lower limbs; modified Thomas test (MTT) was used to measure the flexibility of quadriceps muscle group, active knee extension (AKE) test was used to measure the hamstrings muscle group and, the flexibility of the calf muscle group was tested as described by Norkin and White (2009) (Section 3.3.5).

D) Isokinetic Testing

The strength of knee's extensor and flexor muscle groups were tested for both limbs at 60°/s using an isokinetic dynamometer. Knee flexion/extension ratio (H/Q ratio) is the last criterion in this station and was extracted by dividing the score of concentric (Con) peak torque (PT) of the knee flexor over Con PT of the knee extensor at 60°/s (Section 3.3.6).

E) Neuromuscular Functional Performance Tests

Two tests were performed by the subjects. The first one was one-legged hop for distance and performed as described by Barber et al., (1990). The other test was one-legged triple hop and performed as described by Noyes et al., (1991). Four trials for each leg were performed in each test. The starting leg was randomised and, was fixed for each test (right, right, right, right) . Lastly, the measurements were recorded in metre (m) (Section 3.3.7).

A within-day reliability was established for each criterion before commencing the main study and the studies afterward (Table 4.3). The examined population was a sub-elite athletes group and, the calculated variables were the mean difference (test2-test1), typical error (SD of the difference / √2), standard error of mean (SEM) (SEM = SD / √n), ICC, Pearson's r correlation and coefficient of variance (CV%) (CV= (SD / mean) × 100). The calculation of ICC was done using formulas found in a Microsoft Excel spreadsheet created by Hopkins (2015).

Table 4.3: Reliability results for sub-elite athletes (within-day) of all tested variables for mean difference, typical error, SEM, ICC, CV and Pearson's r correlation (n=10).

Variable	Mean Difference	Typical Error	SEM	ICC	Correlation r =	CV (%)
Flexibility						
Ankle DF 'flexibility'	-0.20	0.34	1.93°	0.99	0.998	6.3
Modified Thomas Test	-0.84	1.73	2.79°	0.97	0.988	2.5
Active Knee Extension test	0.58	0.78	2.53°	0.99	0.991	11.5
Anthropometry						
Leg Length	-0.01	0.03	0.81 cm	0.99	0.999	0.9
Thigh Circumference	-0.01	0.03	1.60 cm	0.99	0.999	3.1
Calf Circumference	-0.02	0.05	0.54 cm	0.99	0.999	1.5
Isokinetic						
Q @ 60°/s 'Strength'	3.6	12.03	11.4 Nm	0.85	0.804	4.8
H @ 60°/s 'Strength'	2.6	2.16	4.4 Nm	0.98	0.968	3.6
NFPTs						
1LH	-0.06	0.05	0.08 m	0.98	0.964	6.4
1LTH	0.03	0.08	0.15 m	0.96	0.981	3.7
CMJ						
1LCMJ Max Force	4.1	1.95	9.6 N	0.93	0.961	5.2
StdBWD Force	0.2	4.99	17.5 N	0.98	0.986	5.5
CMJ Max Force	-5.0	23.48	36.8 N	0.95	0.963	4.6
CMJ Avg Ecc Force	0.2	3.32	17.6 N	0.99	0.995	5.6
CMJ Avg Con Force	-8.6	7.08	32.4 N	0.99	0.997	4.8

Abbreviations; DF= Dorsiflexion; Q @ 60°/s 'strength'= Testing the isokinetic peak torque of quadriceps muscle at 60°/s; H @ 60°/s 'strength'= Testing the isokinetic peak torque of hamstrings muscle at 60°/s, 1LH= one-legged hop, 1LTH= one-legged triple hop, lLCMJ Max Force= maximum force of one-legged countermovement jump, StdBWD= standing body weight distribution, CMJ= countermovement jump, Avg Ecc Force= average eccentric force, Avg Con Force= average concentric force.

The reliability results presented high level of repeatability for all tested criteria (ICC = 0.85-0.99). The results were compared with previous studies and showed similar outcomes. As per flexibility's criteria; Norkin et al., (2009) stated that measurements of ROM of extremities with a universal goniometer have generally found to have good-to-excellent reliability, ICC= 0.89–0.92, Clapis et al., (2008) reported an ICC of 0.96 for the MTT and, for the AKE, DePino et al., (2000) stated ICC of 0.85-0.99. In accordance with the criteria of anthropometrics; an ICC of 0.92 was reported for leg length measurement (Jamaluddin et al., 2011), Soderberg et al., (1996) has stated that the ICC of thigh circumflex measurement was between 0.92-0.98 and, calf's circumflex ICC was reported to be highly reliable by Tschoepl et al., (2000). Graham-Smith et al., (2013) has quantified high reliability for isokinetic testing in both extension and flexion (Concentric phase) at 60°/s (ICC = 0.93 and 0.96, SEM = 11.0 and 5.1 Nm, CV = 4.61% and 4.43 respectively). In term of the criteria of NFPT, there were no difference; as the 1LH test was reported by Greenberger and Paterno (1994) to be ICC = 0.92 to 0.96 and lLTH's ICC = 0.95 (Bolgla & Keskula 1997). Lastly in the CMJ attribute; the reliability of 1LCMJ, maximum, the average of eccentric and concentric forces were ICC = 0.88-0.97 (not specified by Brosky et al., (1999) whether average or maximum force); ICC = 0.92, CV = 4.1% (Hori et al., 2009); CV = 21.3 and 2.7% (Nibali et al., 2015) respectively. Unfortunately, no data were found in the literature for comparison of the reliability of standing body weight distribution that has been generated in this study.

After establishing the norms of the main study, an auxiliary study was conducted using a mixed-athletes group (elite and sub-elite) from different kinds of sports to examine the effect of external load as one of the factors that may or may not affects bilateral asymmetry when performing CMJ (Poster was presented at ESB congress, on Aug 2013, Patras, Greece (APPENDIX: E)). Since the mixed-athlete group is a unique group by itself, specific threshold percentages were generated specifically for this auxiliary study (Tables 4.6-8) by following the same methodology used for the sub-elite athletes group.

As a consequence, sixty three mixed-athletes (57 males; 6 females) were recruited for this specific auxiliary study and, completed the whole bilateral asymmetry analysis bundle. Subjects' demography was represented in Table 4.4.

Table 4.4: Subjects' demography of auxiliary-study (n=63) (Males=57; Females=6)

	Mean	± SD
Age (years)	22.5	4.2
Height (cm)	180.4	9.0
Mass (kg)	83.7	17.4

Subjects performed the exact BAAB that been introduced earlier in section 4.2, except for the CMJ, were athletes have performed additional jumps with a total of nine countermovement jumps (three CMJ, three CMJBW+20% and three CMJBW+40%). The introduction of applying additional load in the form of a weight bar to the athletes when they perform their CMJ could help in investigating the level of impact of external load on their performance in term of BA in lower limbs. A special weight bar which weighs 10kg was used (EZ curl bar) to ensure that the weight of the bar was kept evenly distributed across the shoulders during the CMJ trials (Figure 4.2). Then, based on the weight of the participant, weights were added by splitting it evenly in both sides until reaching a total weight (bar and added weight) of 20% or 40% (depends on the executed test) of each participant. For example, an athlete who weights 60kg would lifts a total of 12kg as additional load for the CMJBW+20% trials and 24kg for the CMJBW+40% trials. Since adding weight in order to investigate it influence on the CMJ criteria for BA was a novel approach, choosing the aforementioned specific was solely based on the clinical judgment of the researcher. Moreover, to ensure the maximum safety of the participants, each participant was asked if he/she was feeling confident while standing with the extra load. Furthermore, before attempting the CMJ trial, two persons were standing next to the participants on both sides for assistance or for emergency in case of the participant might lose balance or unable to complete the whole test. Lastly, the normality was inspected for the tested criteria using the Shapiro-Wilks test.

Figure 4.2: EZ curl weight bar

4.3 Results

The outcomes generated from the battery of testing were a collection of four groups of interest for testing; A) *Anthropometrics,* which covers the static testing of leg length discrepancy, thigh and calf circumflexes discrepancies. B) *Flexibility,* which includes the dynamic testing of the angles on the ankle's dorsiflexion, knee's flexion and extension. C) *Strength*, which has been represented by testing the peak torque of the quadriceps and hamstrings muscles groups during a dynamic task over a single-joint (knee joint) using isokinetic dynamometer at 60°/s. D) *Functional Abilities*, that looks into the bilateral asymmetry difference between lower limbs during the multi-joints dynamic tasks of the 1LH and 1LTH as well as the criteria of CMJ (maximum force, eccentric and concentric average forces), 1LCMJ criteria (maximum force and jump height) and body weight distribution (by standing each leg on a separate force plate).

Table 4.5 has showed the mean and standard deviation of the subjects' performance on each tested criterion in both lower limbs. Each criterion was tested for right and left legs in order to compare the bilateral asymmetry percentages.

After that, Equation 1 was used to calculate the average of absolute asymmetry value percentage for all criteria. Lastly, Equation 2 was utilised to calculate the thresholds percentage as presented in Table 4.5.

Table 4.5: Mean ± SD of sub-elite athlete group's performance of both lower limbs and AAV%. As well as, Threshold % (n=139).

Criteria	R leg Mean±SD	L leg Mean±SD	AAV (%) Mean±SD	Threshold (%)
Ankle DF (°) 'flexibility'	31.1 ± 5.5	31.4 ± 5.6	7.0 ± 6.3	13.3
Q (°) 'flexibility'	124.4 ± 11.7	124.6 ± 11.1	5.5 ± 4.9	10.4
H (°) 'flexibility'	27.4 ± 10.4	28.0 ± 10.2	14.5 ± 10.7	25.2
LLD (cm)	92.4 ± 5.5	92.5 ± 5.4	0.5 ± 0.5	1.0
TCD (cm)	57.0 ± 5.5	56.5 ± 5.4	2.0 ± 1.9	3.9
CCD (cm)	37.5 ± 3.0	37.5 ± 2.9	1.9 ±1.9	3.8
Q @ 60°/s (Nm) 'strength'	195 ± 4	194 ± 4	9.6 ± 8.8	18.4
H @ 60°/s (Nm) 'strength'	102 ± 29	97 ± 26	10.6 ± 8.6	19.2
1LH (m)	1.45 ± 0.32	1.47 ± 0.35	8.9 ± 7.2	16.1
1LTH (m)	4.92 ± 0.94	4.80 ± 1.06	6.9 ± 8.2	15.2
1LCMJ Height (m)	0.128 ± 0.040	0.130 ± 0.041	11.9 ± 7.4	19.3
1LCMJ Max Force (N)	1364 ± 239	1333 ± 210	4.4 ± 5.1	9.6
StdBWD (N)	364 ± 62	358 ± 57	7.6 ± 6.5	14.1
CMJ Max Force (N)	840 ± 173	862 ± 178	6.2 ± 5.3	11.5
CMJ Avg Ecc Force (N)	380 ± 74	362 ± 63	9.0 ± 6.7	15.7
CMJ Avg Con Force (N)	700 ± 149	673 ± 144	6.2 ± 6.4	12.6

Abbreviations; DF= Dorsiflexion; Q @ 60°/s 'strength'= Testing the isokinetic peak torque of quadriceps muscle at 60°/s; H @ 60°/s 'strength'= Testing the isokinetic peak torque of hamstrings muscle at 60°/s, 1LH= one-legged hop, 1LTH= one-legged triple hop, lLCMJ Max Force= maximum force of one-legged countermovement jump, StdBWD= standing body weight distribution, CMJ= countermovement jump, Avg Ecc Force= average eccentric force, Avg Con Force= average concentric force, LLD= Leg length discrepancy, TCD= Thigh circumference discrepancy, CCD= Calf circumference discrepancy.

Interestingly, the highest threshold percentage generated in Table 4.5 was hamstrings flexibility by scoring 25.2% and, followed by knee flexion at 60°/s by scoring 19.2%. These percentages showed a wide margin of bilateral asymmetry between the right and left lower limbs without affecting the optimal functional level of an athlete as suggested in the literature. In contrast, the leg length discrepancy has scored the lowest threshold percentage by scoring 1.0% only. Such score allows for only a very narrow margin of bilateral asymmetry in performance between limbs.

In accordance to the auxiliary study, that examined CMJ across different weights load, the results showed that, bilateral asymmetry was clearly evident throughout all tested criteria as shown in Tables 4.6-8. Interestingly, the level of bilateral asymmetries exhibited similar percentages across trials for each tested criterion except for the average concentric force as the threshold percentages in this auxiliary study has varied from 11.8 % to 24.9 % as seen in Table 4.8.

Table 4.6: Threshold percentages of anthropometrics, flexibility and isokinetic criteria of auxiliary study. As well as, the mean ± SD of right and left legs performances and absolute asymmetry value percentages (AAV%) (n=63).

Criteria	**R** **Mean±SD**	**L** **Mean±SD**	**AAV (%)** Mean±SD	**Threshold (%)**
Anthropometry				
Leg Length (cm)	95.5 ±5.74	95.6 ±5.67	0.6 ± 0.6	1.2
Thigh Circumference (cm)	58.3 ±6.7	58.1 ± 6.8	2 ± 1.7	3.7
Calf Circumference (cm)	38.5 ±3.2	38.4 ±3.2	1.4 ± 1.2	2.6
Flexibility				
Modified Thomas Test (°)	126.3 ±12.5	125.9 ±12.5	6.9 ± 5.6	12.5
Active Knee Extension Test (°)	30.5 ±10.5	30.7 ±9.3	14.6 ± 11.9	26.5
Ankle DF Flexibility (°)	31.0 ±5.5	31.4 ±5.6	6.0 ± 6.1	12.1
Isokinetic				
Q @ 60°/s (Nm)	225 ± 61	228 ± 58	10.4 ± 9.4	19.8
H @ 60°/s (Nm)	127 ± 40	119 ± 34	11.5 ± 8.3	19.8

Table 4.7: Threshold percentages of NFPTs and 1LCMJ criteria of auxiliary study. As well as, the mean ± SD of right and left legs performances and absolute asymmetry value percentages (AAV%) (n=63).

Criteria	**R Mean±SD**	**L Mean±SD**	**AAV (%)** Mean±SD	**Threshold (%)**
NFPTs				
1LH (m)	1.70 ±0.33	1.69 ± 0.33	6.9 ± 6.3	13.2
1LTH (m)	5.62 ± 0.84	5.70 ± 0.92	4.6 ± 4.7	9.3
1LCMJ				
1LCMJ Height (m)	0.141 ± 0.04	0.146 ± 0.04	10.1 ± 8.2	18.3
1LCMJ Max Force (N)	1534 ± 295	1544 ± 318	4.9 ± 4.7	9.6

Furthermore, Table 4.8 has shown interestingly that, the average eccentric force threshold percentage has exhibited the opposite pattern as the athlete started to display more symmetrical weight distribution behaviour after the added weight of 20 and 40% and that was reflected on their threshold percentages as well. Lastly, when examining the average concentric force threshold percentage across all trials, it was found that CMJBW+40% have exhibited by far the greatest BA threshold percentage.

Table 4.8: Auxiliary study's threshold %. As well as, Mean ± SD of performance and AAV% of CMJ criteria across trials (CMJ, CMJBW+20% and CMJBW+40% (n=63). One-way ANOVA test was performed across trials for the four CMJ criteria. Significance was set at $p \leq 0.05$ (Significant values were highlighted with (*)).

Criteria	R Leg Mean±SD	L Leg Mean±SD	AAV % Mean±SD	Threshold (%)
CMJ				
StdBWD Force (N)	415 ± 87	408 ± 81	6.5 ± 4.6	11.1
Maximum Force (N)	934 ± 191	966 ± 193	5.9 ± 5.7	11.6
Avg Ecc Force (N)	427 ± 88	413 ± 84	8.4 ±6.6	14.9
Avg Con Force (N)	779 ± 161	758 ± 170	6.8 ± 6.9	13.7
CMJBW+20%				
StdBWD Force (N)	496 ± 102	485 ± 93	6.9 ± 4.5	11.4
Maximum Force (N)	991 ± 205	1014 ± 202	5.4 ± 4.9	10.3
Avg Ecc Force (N)	502 ± 103	488 ± 98	9.2 ± 5.2	14.4
Avg Con Force (N)	826 ± 175	805 ± 181	6.0 ± 5.8	11.8
CMJBW+40%				
StdBWD Force (N)	576 ± 123	556 ± 111	7.6 ± 5.0	12.6
Maximum Force (N)	1041 ±233	1054 ± 229	5.3 ± 5.6	10.9
Avg Ecc Force (N)	587 ± 120	562 ± 112	8.9 ± 6.0	14.9
Avg Con Force (N)	1043 ±237	842 ± 199	18.6 ± 6.3	24.9*

Interestingly, the mean difference between trials of average concentric force criteria was found to be statistically significant using the one-way ANOVA test (F (2, 186) = 78.01, p = 0.000) and, post-hoc test has located the significance between the mean difference of CMJBW+40% from the other two trials (Table 4.9). Significance for LSD post-hoc test was set at (Alpha = 0.05). Furthermore, Figure 4.3 has illustrated a summary of the differences in the threshold percentages of each criterion after applying external loads across the countermovement jump trials (body weight only, additional 20 and 40% of body weight).

Table 4.9: Identifying the trial groups with significance difference in threshold% on Avg Con Force criterion. Significance values were highlighted with (*).

One-way ANOVA / POSTHOC=LSD ALPHA (0.05).					
Dependent Variable	**Trials**		**Mean Difference**	**Std. Error**	**Sig.**
Average Concentric Force	CMJBW+40%	CMJ	11.793	1.130	0.000*
		CMJBW+20%	12.636	1.130	0.000*

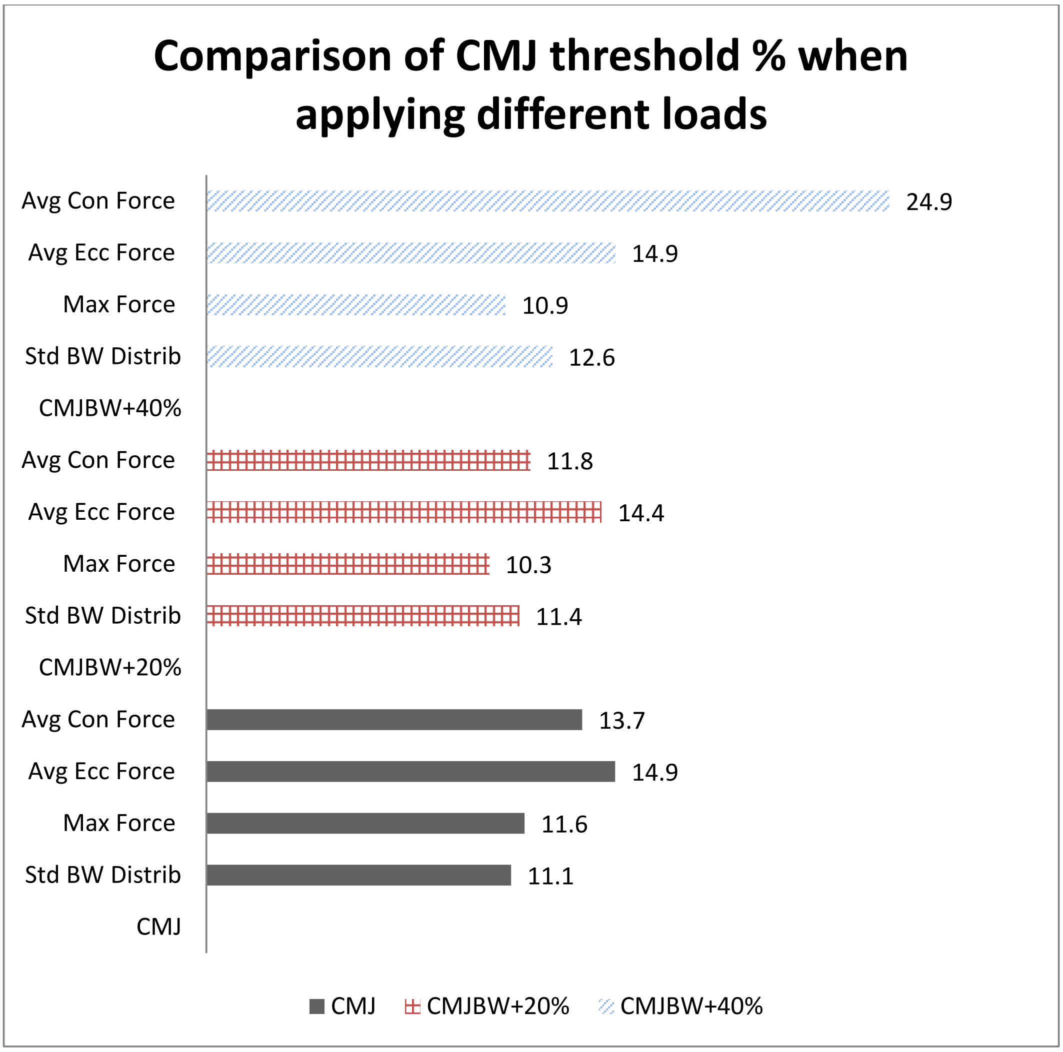

Figure 4.3: Comparison between threshold percentages of CMJ, CMJBW+20% and CMJBW+40% (n=63).

Another descriptive statistical analysis using the generated threshold percentages utilised to diagnose subjects whom agreed to have a like-like asymmetry agreement by utilising Equation 3. The association was executed on the bilateral CMJ criteria across trials (CMJ, CMJBW+20% and CMJBW+40%) to examine the level of asymmetry agreement percentage when adding extra loads (between the CMJ's trials) as seen in Table 4.10.

Table 4.10: Asymmetry agreement in diagnosis of CMJ across trials (n= 63).

Standing Body Weight Distribution			
Trial	**CMJ**	**CMJBW+20%**	**CMJBW+40%**
No. of Asymmetry	10	11	12
Association	CMJ vs. CMJBW+20%	CMJ vs. CMJBW+40%	CMJBW+20% vs. CMJBW+40%
No. of Agreement	50	47	54
Asymmetry Agreement (%)	79.4	74.6	85.7
Maximum Force			
Trial	**CMJ**	**CMJBW+20%**	**CMJBW+40%**
No. of Asymmetry	8	7	5
Association	CMJ vs. CMJBW+20%	CMJ vs. CMJBW+40%	CMJBW+20% vs. CMJBW+40%
No. of Agreement	58	60	59
Asymmetry Agreement (%)	92.1	95.2	93.7
Average Eccentric Force			
Trial	**CMJ**	**CMJBW+20%**	**CMJBW+40%**
No. of Asymmetry	5	10	12
Association	CMJ vs. CMJBW+20%	CMJ vs. CMJBW+40%	CMJBW+20% vs. CMJBW+40%
No. of Agreement	50	48	53
Asymmetry Agreement (%)	79.4	76.2	84.1
Average Concentric Force			
Trial	**CMJ**	**CMJBW+20%**	**CMJBW+40%**
No. of Asymmetry	7	5	8
Association	CMJ vs. CMJBW+20%	CMJ vs. CMJBW+40%	CMJBW+20% vs. CMJBW+40%
No. of Agreement	59	52	54
Asymmetry Agreement (%)	93.7	82.5	85.7

Lastly, the results in Table 4.10 showed that, asymmetry agreement percentages were similar in all CMJ criteria across trials. Such results reveals that diagnosis based Asymmetry agreement percentages showed similar finding when examining the CMJ criteria across trials.

4.4 Discussion

The purpose of this study was to investigate novel approaches when examining bilateral asymmetry by determining threshold percentages of key criteria in the lower limbs. The sub-elite athletes' threshold percentages were calculated from the averages of absolute asymmetry difference of eighteen criteria that been formulated from six different attributes (Anthropometric, strength, flexibility, NFPT, CMJ and 1LCMJ). BA% was examined on the absolute difference of each tested individual. Whereas, previously, examination was based on differentiating between right/left or non-dominant/dominant limbs then averaging the performance of each leg separately and calculating their asymmetry index (Newton et al., 2006) which tend to show no asymmetry. Therefore, normative data in the form of AAV percentages for different lower-limb characteristics were established. Such approach has revealed tailored-made threshold percentages for each criterion and improving on previous bilateral asymmetry percentages in lower limbs found in literature.

The flexibility of hamstrings muscle group has scored the highest threshold point among the rest of the all criteria. Such threshold enable athletes to enrol quicker into their training regime if they had an injury that affected their BA. For example, early return to his/her training programme after a hamstring injury while still being involved in the plan of care by the rehabilitation team in order to reach their finest level before injury. This early involvement can be safely achievable only if the demand to exact symmetry between limbs is less obligatory.

On the other hand, when the threshold is quite low (For example, leg length discrepancy), it would take a longer rehabilitation programme to correct such asymmetry before athletes be able to enrol into their training regime more effectively and safely and that would allow athletes to reach their optimum performance. Moreover, the application of threshold percentages when examining bilateral asymmetry has showed more meaningful outcome when the criteria of BA been examined. For example, when diagnosing LLD between lower limbs, if the arbitrary percentage of 15% was implement as mentioned in the literature; there will be an acceptable difference of up to 15 cm (assuming one of the athlete's leg is 100 cm long) before exceeding the threshold. In reality, a LLD of 15 cm is considered as a deformity and might need therapeutic or even surgical intervention before competing in sport. Thankfully, the generated threshold percentages in this study (Table 4.5) gave an exact cut-off value for a number of key criteria in the lower limb to diagnose BA. As a result, setting independent threshold percentages for each criterion could provide clinicians with precis clinically relevance assessment tool to diagnose athletes for BA or monitoring their rehabilitation progress (tracking plan of care to increase flexibility).

This study had several advantages. Firstly, it was the first study to examine BA by identifying threshold percentages of key criteria in lower limbs. This was achieved by identifying the absolute difference between limbs. Previous studies (Goslin and Charteris, 1979; Hvid et al., 1981; Holmes and Alderink, 1984; Berg et al., 1985; Beckett et al., 1992; Astrom and Arvidson, 1995; Livingston and Mandigo, 1997; Sobel et al., 1999; Rahnama et al., 2005) have utilised one-way ANOVA or/and correlation coefficients tests to identify whether or not significant differences existed between left and right limbs (or dominant vs. non-dominant). The statistical analysis approach used in this study has prevented the nullifying effect that has occurred in studies such as Newton et al., (2006). Secondly, this study did not diagnoses asymmetry based on preferences such as dominant/non-dominant, strongest/weakest leg due to the inherent weaknesses of such methods (i.e., cyclists, do not favour one leg over the other in term of dominancy). Thirdly, it has a large sample size (n=139), which is a superior advantage, when compared with previous studies such as Newton et al., (2006) who used smaller sample size (n=14). The most important element of this study was, establishing clinical cut-off points for a variety of lower-limb characteristics. No study has yet established normative values for absolute asymmetry for a range of anthropometric lower limb characteristics, as done in this study. These AAV are far more sensible than an arbitrary value of 10% or 15% used throughout the literature. It would be superior to use these AAVs in clinical assessment of lower-limb's BA. Therefore, establishing accurate threshold percentages would significantly improve the quality of rehabilitation programmes provided to the athlete by assessing each variable individually and objectively (i.e. one-legged triple hop 6.9 ± 8.2%). Moreover, if an arbitrary value of 10%, 15% or even 20% was used in clinical assessment, one could under or over-diagnose asymmetry in athletes thus, it was imperative to utilise an accurate threshold difference when examining BA in lower-limbs. Furthermore, another good example to support that suggestion of using threshold percentages for more accurate diagnosing of BA in athletes is, if the cut-off of 10% suggested by previous researchers (Grace et al., 1984; Kannus, 1994; Sherry and Best, 2004) was utilised in clinical practice for examining isokinetic strength testing, a number of subjects would be under-diagnosed with bilateral asymmetry for quadriceps PT and over-diagnosed for hamstrings PT. Moreover, if the 15% cut-off suggested by other researchers (Barber et al., 1990; Knapik et al., 1991; Wilk et al., 1994; Petschnig et al., 1998; Newton et al., 2006; Impellizzeri et al., 2007) was carried out for analysis, subjects would be under-diagnosed again. As a consequence, misdiagnosing athletes with higher asymmetry percentages would potentially oversight the opportunity to properly enrolled them in a proper rehabilitation programme which may reduce their injury risk. Nevertheless, this study has produced similar yet more specific threshold percentages in the category of NFPT ability as Noyes et al., (1991) quoted 15% difference to be significance and many authors and rehabilitation protocols utilised it (1LH= 16.1; 1LTH= 15.2 %).

Fourthly, the results from this study revealed that BA exists in all criteria (Table 4.5). Based on the assumption that one-third of a population exhibits bilateral asymmetry (the area outside the normal distribution curve, which is approximately 31.8%) it would appear that adopting the absolute asymmetry value could enable sufficient detection and diagnosis of asymmetry between lower limbs and serves as a clinical cut-off point. Thus, evaluating the AAV percentage has shown an objective and more accurate tool to assess asymmetry. Consequently, the inherent problems with specifying dominance and erroneous statistical analyses are not concerns when diagnosing BA in this novel statistical analysis method.

Furthermore, bilateral asymmetry were relatively consistent for each subject during calculating the ICC tests and has showed that the measurements were highly repeatable. It was important to reveal that asymmetries are not random and maintain a consistent magnitude within-session. Moreover, the results presented in Table 4.3 has showed that all measurements strongly associated with previous researches and all of them exhibited high repeatability as categorised by Field, (2013).

Regarding the absolute asymmetry value percentage of maximal force during CMJ, the results of this study (5.9 ± 5.7 %) corroborate with the data by Newton et al. (2006) who found a difference of 5.68 ± 3.95% in BA. Even using only one force-plate, Impellizzeri et al. (2007) reported that the average lower-limb strength asymmetry value was 0.8%, which was far off from the findings of Newton et al., (2006) or this study. It was somewhat interesting to observe a difference in force production of 11.5% for the maximum force of CMJ as it was a symmetrical bilateral activity and athletes have reported good experience in performing it. However, considerable and meaningful differences were evident in the criteria of CMJ. The results of isokinetic strength assessments can only be compared with the studies of Impellizzeri et al. (2007) and Newton et al. (2006) for the angular velocity of 60°/s since this study has used the same aforementioned speed. As a consequence, the means of BA knee extension and flexion of the aforementioned cited studies were 8.26% and 13.51% respectively, the mean and standard deviation of this presented study for knee extensors were (9.6 ± 8.8) and knee flexors (10.6 ± 8.6 %), thus this study identified similar BA for the mean only. However, these studies assessed dominant/non-dominant leg, which as discussed before, leads to erroneous conclusions. Hoffman et al., (2007) examined healthy populations and reported an asymmetry index of 8 % for maximum force of the one-legged CMJ, which was lower than the values in this presented study (9.6 %). However, this study has similar finding with Newton et al., (2006) who found an asymmetry of 9.7% for maximum force of one-legged CMJ.

The results from the auxiliary study have a number of thought-provoking points for discussion. As it firstly, the dramatic increased in BA threshold percentage of the average force could be due to embedded bilateral asymmetries from other exceeded BA criteria in the lower limbs and, once the body has provoked by placing it under stress (i.e. external load), a bilateral asymmetry was unveiled. As a result, provoking the musculoskeletal system by means of external loads would manipulate the body's kinetics and consequently, shifting a number of key criteria in the lower limbs from being symmetrical to being asymmetrical or vice versa during a functional behaviour task (i.e. countermovement jump or running gait). Such assumption would facilitate further investigations into other criteria that may contribute into altering bilateral asymmetry in lower limbs. For example, in case of excessive increases of BA in the average force of countermovement jump during the CMJBW+20% in athletes, the rehabilitation team should examine the rest of the attributes (flexibility, strength and anthropometric) and identify if one or more of the tested criteria exceeded the threshold percentage, as it could have a role in explaining the exhibition of such abnormality.

Secondly, unlike the threshold percentage of average force during the whole countermovement jump trial, the average eccentric force has exhibited an opposite pattern during the CMJ trials as there was a considerable shift of BA from being asymmetric to be more symmetric which contradicts the result of BA threshold of average force criteria. An increased bilateral asymmetry during a CMJ after adding a weight could be as a result of the athletes having leg length discrepancy over the proposed threshold percentage which caused him to lean more on the shorter leg during the jump. Another possibility is, that quadriceps muscle group may produce more torque during the CMJ which explain the increase average force generated on one force plate over the other. Unfortunately, this study did not measure the effect of timing nor muscle recruitment when performing CMJs, as these two factors (Figure 1.1) could answer the reason of why athletes became more asymmetric with extra heavy loads. An explanation to this phenomenon could be due to the fact that athletes with LLD would produce more torque on one leg over the other to control their body ascending or perhaps, an excessive BA in muscle power would cause athletes to have a different muscle's initiation time between limbs.

Lastly, performing heavy resistive exercises (i.e., two-legged squatting) may alter the threshold percentages of the countermovement jumps parameters (standing body weight distribution, average concentric and eccentric forces and maximum forces). Thus, different loads where incorporated during CMJ when examining BA since the majority of recruited athletes in this thesis performed their resistive training modalities utilising their body weight only. As a consequence, adding extra load to the mixed-athlete group appeared to have a significance difference in CMJBW+40% trial and for average concentric force only. This asymmetrical shift at this specific trial could be as a result of other embedded asymmetries such as differences in muscle strength or anthropometric discrepancy which forces the body structure to lean more on one side over the other to perform the jump as symmetrical as possible. The similar result of the CMJ parameters across trials (except average concentric force during CMJBW+40%) suggests that, using the body weight only during CMJ was appropriate to diagnose BA. Furthermore, the examination of asymmetry agreement has also supports this recommendation as Table 4.10 has revealed that the percentages of all tested agreements were equal or in excess of 75%. Such result indicates that three out of four (or even higher) subjects had the same diagnosis of asymmetry with increasing loads. Therefore, it was felt that the use of body weight only when testing the countermovement jump's parameters for any bilateral asymmetry was appropriate.

4.5 Conclusion

In conclusion, bilateral asymmetries in lower limbs were evident in healthy athletes' population regardless to their effect in performance. The asymmetries in performance have varied between functional tasks such as while performing CMJ and other criteria found in anthropometric, flexibility and strength measurements. The threshold percentages produced in this study should serve as critical cut-off values in sports rehabilitation and strength and conditioning coaching. If the percentages of BA were found to be more than the threshold it would raise concerns regarding potential increased injury risk or reduction in performance.

This presented study overcomes the shortcomings of previous studies diagnosing asymmetry based on comparing mean of both lower limbs and then calculating the difference using symmetry indexes found in literature. Thus, the threshold percentages generated from the absolute asymmetry values could serve as a more meaningful and precise clinical cut-off points to diagnose bilateral asymmetry. Furthermore, values falling outside each boundary can be considered abnormal and, interestingly, many of them were not similar to the 15% commonly used in the literature to define bilateral asymmetry in performance.

Several authors have stated that dynamic functional capacity cannot be ascertained from the isokinetic strength testing (Daniel et al., 1982; Mangine, 1990), and the results of this study support this belief. Therefore, CMJ on a double force-platform seems to be more appropriate to identify lower-limb BA. However, isokinetic measurements are still important procedures for the assessment of muscular force characteristics, especially after injuries and during the rehabilitation process as one attribute (for example, neuro-functional performance test) may not be sufficient in the dynamic assessment of a patient's functional level. Thereby, several tests may be required to attain an accurate assessment of the athletes that cover their physical examination, bilateral asymmetry in performance and functional tasks to stands on their readiness to return to competition in sport. This suggestion was consistent with the beliefs of previous researchers (Harter et al., 1988; Gray et al., 1992; Theoharopoulos et al., 2000), who stated that, there is no one single adequate measure of function that assess the physical performance of athletes.

Moreover, this study has shown similar findings when the ICC of the tested criteria were examined. The verification of the tested data in order to extract the norms which was a major aim of executing this thesis and has shown a strong within-session repeatability measures and that was highly agreed with the results showed by previous studies.

Furthermore, the auxiliary study has two fruitful advantages, firstly, it has a novel approach in investigating the effect of external loads during CMJ. The investigation has benefited from deeply examining the CMJ by splitting the CMJ trial into eccentric and concentric phases which was a gain a novel approach. Such methodology showed superior understanding over the standard examination of CMJ trial as whole (CMJ average jump) which has been practiced in previous researches (Newton et al., 2006 and Impellizzeri et al., 2007). Such approach, has provided further insights about the possible factors that might affect the descending phase as well as the ascending one in the whole CMJ trial. Secondly, the investigation of how the body kinetics behave when the musculoskeletal structure is being stressed (by applying external loads on it) has unveiled that it is appropriate to examine BA of all CMJ parameters based on the body weight only as the results from across CMJ trials exhibited the similar level of BA (except of average concentric force during CMJBW+40% trial) as seen in Figure 4.3. Lastly, the results from the asymmetry agreement test suggest that this novel approach had offered a further insight and better understanding when examining the association between variables and not to be constrained with only two statistical analyses tests that examines BA between lower limbs across different trails (i.e., one-way ANOVA and Pearson's correlation tests).

Finally, demands toward reaching supreme performance levels in sport was and will be a key goal for all athletes. Therefore, sport rehabilitation teams tend to tailor generalised assessment protocols to meet their sport-specific demands based on the assumption that BA in elite-athletes differ from sport to another. For that, study two (Chapter 5) has generated sport-specific threshold percentages for the same aforementioned key criteria aiming to examine the differences between thresholds.

5.0 STUDY TWO

Title: Establishing norms for bilateral asymmetry in lower limbs of elite-athletes in four specific-sports.

5.1 Introduction

Since 776 BC, ancient Roman athletes started competing in Olympics' games and, the interest to acquire superior physical capabilities is believed to start growing up ever since. Nowadays, the sport industry has been thriving enormously, with contracts of elite soccer players reaching (Forbes, 2014) up to 133 million pounds over five years (Cristiano Ronaldo). It is vital to ensure that these elite-athletes perform exceedingly as it should be expected from their clubs. Such interest increases the scope of developing tailored rehabilitation programmes that provide sports club with more sport-specific training techniques as well as lessen the rehabilitation programmes period possibly by using sophisticated diagnostic equipment, emphasising evidence-based training methods and utilising focused assessment tools. It is thought that accurate diagnosis and intervention of BA in lower limbs could help reducing injury risk and improve athletes' performance however such speculation is still inconclusive. Thus, this study has focused the light on four sport-specific groups of elite-athletes and generated norms for bilateral asymmetry in lower limbs. The four chosen ones were as follow; track and field (Athletic), Rugby, Soccer and Cricket. Interestingly, three out of four of those sports were first reported internationally in United Kingdom, as Cricket (the oldest reported one) was first referenced in 1598. The last two games Rugby and Soccer were referenced later in 1823 and 1863 respectively.

Several studies have investigated bilateral asymmetries in athletes' population either to promote the athlete's outcome measures or predict/prevent injury risk (Orchard et al., 1997; Theoharopoulos et al., 2000; Croisier et al., 2003; Rahnama et al., 2005; Impellizzeri et al., 2007; Croisier et al., 2008; Gioftsidou et al., 2008; Schiltz et al., 2009; Fousekis et al., 2010). Unfortunately, those studies can't be compared between each other as they lack in coherence as the variance between them stretches from; different methodology structures, numbers of chosen criteria, statistical analysis approach and type of population. Unlike the previous study (Chapter 4), this study investigates BA in sport-specific groups of athletes which is still an uncharted field to be examined due to the lack of agreement on critical thresholds for BA. Another obstacle is that, the literature review has only revealed little information about how BA varies between sports as the investigated sport-specific elite-athletes' groups were done until this moment so far in soccer (Orchard et al., 1997; Croisier et al., 2003; Rahnama et al., 2005; Impellizzeri et al., 2007; Croisier et al., 2008; Gioftsidou et al., 2008; Fousekis et al., 2010) and basketball (Theoharopoulos et al., 2000 and Schiltz et al., 2009) only.

As it well-known, injured elite-athletes due to functional dis-capabilities are not likely to be under spotlights when the transfer's market starts to open it season. As a consequence, for that reason, joining the race of optimising elite-athletes' performance and/or decrease their susceptibility to risk of injury is favourable. Indeed, several practitioners in general have tailored specific training programmes that include repeated power-training and heavy-resisted training protocols in order to enhance their elite-athletes' performance or even for specific muscle groups to improve certain repeated movements (Bloomfield et al., 1990; Veliz et al., 2014). Therefore, it was fundamental to develop sport-specific threshold percentages of key criteria for BA in lower limbs to monitor functional dis-capabilities as it crucial when assessing elite-athletes' performance. Clinically established cut-offs percentages for sport specific groups of athletes could be highly beneficial as it can be utilised as a valuable assessment tool that highly increase clinicians' ability to diagnose and identify any causative factors of functional dis-capability. Furthermore, acknowledging the variance of lower limbs criteria that it has the potential to differ substantially from side-to-side would assist clinicians and researchers to determining the extent to which there would be a potential risk of injury.

Thus, the aim of this study was to establish true sport-specific thresholds for typical levels of bilateral asymmetry in four different kind of sports using the novel approach introduced previously (Chapter 4). The proposed approach has sat threshold percentages of certain key criteria for BA in lower limbs aiming for a safer practice for elite athletes. This study has duplicated the same methodological approach of study one (Section 4.2).

5.2 Methodology

Seventy-nine injury-free elite athletes were participated in this study. The subjects' demographics for the average ± SD of age, height and mass were 22 ± 4.7 year, 181.7 ± 8.7 cm, 86.1 ± 18 kg respectively (Males= 71 and Females= 8). Each sport club has received a copy of the patient's information sheet (Appendix C) after accepting to join the testing in order to understand the procedure of the bilateral asymmetry analysis bundle (BAAB) and, to schedule the testing day in a convenient day for the athletes to eliminate the effect of fatigue on them. All athletes were asked to complete a consent form (Appendix B1) prior to being investigated.

The same methodological approach was implemented when testing those sport-specific subjects along with the same statistical analysis approach tin order to generate the AAV percentages for each sport group. Table 5.1 showed that, rugby players were the most recruited participant in this study as they were almost forty athletes. On the other hand, only ten athletes were recruited in the track and field group. Such differences arose due to the easy recruitment when players are from the same club. Unlike track and field athletes, were individual contacts were made to arrange for testing.

Table 5.1: Number of elite-athlete subjects within each sport (n= 79).

Sport	No. of Subjects
Athletic	10
Cricket	11
Soccer	20
Rugby	38

The BAAB illustrated previously in section 4.2 was carried on to be executed toward elite-athletes in this study and, no alteration was done to it by any means, since the goal of this study was to generate sport-specific norms for elite-athletes for the sake of safe practice or/and optimising performance. For that, after familiarisation of the testing protocol followed by worming up, all athletes completed the whole BAAB on the same day. Although the coaches of the athletes were around during testing, athletes were asked to honestly report any injuries (that if the rehab team know about, may affect their chance to participate during competition). Nevertheless, all gathered data were kept safe and were revealed only to the designated rehabilitation member. Since the BAAB was proposed as part of a general screening testing protocol to the sport teams, all tested athletes whom did not meet the inclusion criteria were excluded as their records may affect the generated outcome data (i.e. recent ACL reconstruction surgery). A one-way ANOVA test) was used to compare the bilateral asymmetry values for all variables between sports as there were four sets of group to be examined (mean difference between groups). A Bonferroni post-hoc test was subsequently used to locate any significant differences between the groups. Statistical significance was set at $p \leq 0.05$.

5.3 Results

The bilateral asymmetry analysis bundle consists of testing a collection of four attributes of interest; A) *Anthropometrics*. B) *Flexibility*. C) *Strength*. D) *Functional Ability*. Table 5.2, demonstrates the mean performance of each criterion executed by all four groups except for the 1LCMJ criterion in the track and field's group thus, the criteria of 1LCMJ will not be included during the comparison between sport groups as not all the groups managed to complete that test.

Table 5.2: Mean ±SD subject's demography and *Performance* of elite-athletes. (Cricket, n= 11; Rugby, n= 38; Soccer, n= 20; Track and field (Athletic), n= 10) (Total n= 79).

Criteria	*Mean Performance ± SD*							
	Cricket		Rugby		Soccer		Athletic	
	R	L	R	L	R	L	R	L
Age (year)	25.0 ± 3.8		23.6 ± 4.6		18.5 ± 3.3		19.7 ± 2.2	
Height (cm)	185.5 ± 6.9		185.5 ± 6.7		177.0 ± 7.9		172.3 ± 8.5	
Mass (Kg)	80.0 ± 6.9		101 ± 11.9		71.5 ± 9.2		65.4 ± 8.7	
Ankle DF 'Flexibility' (°)	32.4 ± 3.5	32.8 ± 4.7	29.1 ± 5.3	30.1 ± 5.0	30.1 ± 5.3	29.5 ± 5.2	28.7 ± 2.9	29.3 ± 5.7
MTT(°) 'Flexibility'	129.4 ± 9.3	129.6 ± 10.0	123.4 ± 11.0	129.6 ± 10.0	126.0 ± 7.0	128.8 ± 6.0	125.9 ± 12.0	131.7 ± 7.9
AKE (°) 'Flexibility'	28.8 ± 6.7	28.2 ± 8.5	25.8 ± 8.7	28 ± 8.1	23.8 ± 9.8	23.9 ±10.0	16.1 ± 7.0	18.2 ± 8.0
LLD (cm)	97.7 ± 4.7	97.8 ± 5.1	98.3 ± 4.6	98.4 ± 4.7	92.8 ± 5.5	92.9 ± 5.4	93.2 ± 3.0	93.1 ± 3.3
TCD (cm)	55.8 ± 7.3	55 ± 7.9	64.3 ± 4.4	64.2 ± 4.0	55.3 ± 4.3	54.7 ± 4.1	55.2 ± 3.8	54.7 ± 3.6
CCD (cm)	37.1 ± 2.0	37.2 ± 2.1	41.3 ± 3.1	41.1 ± 2.9	37 ± 2.6	36.7 ± 2.6	35.8 ± 2.8	36 ± 2.7
Q @ 60°/s (Nm) 'Strength'	225 ± 43	227 ± 38	270 ± 52	274 ± 44	215 ± 35	208 ± 40	178 ± 43	177 ± 55
H @ 60°/s (Nm) 'Strength'	119 ± 23	110 ± 17	161 ± 26	155 ± 20	86 ± 42	81 ± 45	113 ± 33	113 ± 47
1LH (m)	1.65 ± 0.2	1.67 ± 0.1	1.86 ± 0.2	1.88 ± 0.2	1.81 ± 0.2	1.88 ± 0.2	2.18 ± 0.3	2.18 ± 0.3
1LTH (m)	5.62 ± 0.4	5.95 ± 0.4	6.13 ± 0.6	6.19 ± 0.7	5.89 ± 0.4	5.96 ± 0.5	5.62 ± 0.4	5.95 ± 0.4
1LCMJ Height (m)	0.148 ± 0.022	0.158 ± 0.023	0.149 ± 0.035	0.155 ± 0.036	0.184 ± 0.026	0.186 ± 0.04	N/T	
1LCMJ Max Force (N)	1395 ± 156	1426 ± 189	1815 ± 260	1851 ± 264	1484 ± 238	1524 ± 268	N/T	
CMJ Height (m)	0.311 ± 0.046		0.327 ± 0.049		0.351 ± 0.06		0.357 ± 0.041	
CMJ Power (W) Con-phase	3908 ± 883		4959 ± 601		3753 ± 634		3482 ± 808	

Cont.	*Mean Performance ± SD*							
Criteria	Cricket		Rugby		Soccer		Athletic	
	R	L	R	L	R	L	R	L
StdBWD Force (N)	393 ± 47	390 ± 56	495 ± 68	491 ± 62	358 ± 55	353 ± 42	337 ± 50	327 ± 49
CMJ Max Force (N)	867 ± 104	856 ± 85	1127 ± 158	1142 ±163	909 ± 155	904 ± 171	868 ± 147	831 ± 134
CMJ Avg Ecc Force (N)	412 ± 41	404 ± 31	492 ± 72	496 ± 61	367 ± 64	348 ± 43	340 ± 50	333 ± 60
CMJ Avg Con Force (N)	702 ± 70	707 ± 82	904 ± 131	907 ± 136	730 ± 118	725 ± 135	710 ± 130	683 ± 125

Abbreviations; DF= Dorsiflexion; Q @ 60°/s 'strength'= Testing the isokinetic peak torque of quadriceps muscle at 60°/s; H @ 60°/s 'strength'= Testing the isokinetic peak torque of hamstrings muscle at 60°/s, 1LH= One-legged hop, 1LTH= one-legged triple hop, lLCMJ Max Force= Maximum force of one-legged countermovement jump, StdBWD= Standing body weight distribution, CMJ= countermovement jump, Avg Ecc Force= Average eccentric force, Avg Con Force= Average concentric force, MMT= Modified Thomas test, AKE= Active Knee Extension, LLD= Leg length discrepancy, TCD= Thigh circumference discrepancy, CCD= Calf circumference discrepancy.

Eventually, the generated performance data in Table 5.2, allowed for disclosing the initial outcome measure by calculating the BA of each criteria in the form of absolute asymmetry value percentages within each sport-specific group of athletes. The calculation of AAV% for each criteria was based on Equation 1 (Section 3.3.1), as it equals the difference between right and left lower limb [AAV% = Abs [((right leg score) – (left leg score)) / (Max score of either leg)] x100]. The results were presented in Table 5.3.

Moreover, a one-way ANOVA test was executed on the generated data to compare the mean difference between sport groups. Data were tested for significance based on all tested criteria (Table 5.3). The criterion for one-way ANOVA's significance was set to be $p \leq 0.05$.

Table 5.3: Mean ±SD of AAV % of all criteria for each sport-specific group (n= 79). One-way ANOVA test significance was set at $p \leq 0.05$. Data with significance values were highlighted with (*).

	Mean AAV ± SD %			
Criteria	**Cricket**	**Rugby**	**Soccer**	**Athletic**
Ankle DF 'Flexibility'	4.6 ± 3.5	6.9 ± 7.6	7.4 ± 7.4	11.6 ± 6.2
MTT 'flexibility'	6.2 ± 6.1	6.4 ± 5.5	5.1 ± 3.5	5.9 ± 4
AKE 'flexibility'	13 ± 9.5	16.9 ± 14.4	17.1 ± 12.5	23.9 ± 14.2
LLD	0.4 ± 0.4	0.6 ± 0.6	0.6 ± 0.5	0.4 ± 0.6
TCD	1.8 ± 2.5	1.7 ± 1.6	2.1 ± 1.8	1.3 ± 1
CCD	1.8 ± 1	1.5 ± 1.5	1.3 ± 1.3	1.1 ± 1.2
Q **@ 60°/s 'Strength'**	13.8 ± 11.1	7.9 ± 7.1	9.2 ± 6.2	7.1 ± 6
H **@ 60°/s 'Strength'**	12 ± 7.5	9.7 ± 6.8	17.5 ± 15.4*	7.3 ± 6.3
1LH	7.8 ± 10.1	6 ± 5.5	5.5 ± 4.3	2.8 ± 1.9
1LTH	6.3 ± 7	3.2 ± 2.6	3.3 ± 3.0	2.0 ± 1.9
1LCMJ Height	10.6 ± 11.2	7.5 ± 6.9	13.5 ± 8.3	N/T
1LCMJ Max Force	4.1 ± 3.7	5.1 ± 4.4	4.8 ± 4.2	N/T
StdBWD Force	5.1 ± 4.0	6.1 ± 4.7	5.8 ± 5.6	5 ± 2.1
CMJ Max Force	4.8 ± 4.5	4.8 ± 3.7	3.0 ± 2.0	4.3 ± 3.7
CMJ Avg Ecc Force	6.4 ± 6.6	6.9 ± 5.9	5.9 ± 4.3	8.5 ± 3.5
CMJ Avg Con Force	5.2 ± 5	5.6 ± 4.4	2.7 ± 1.7	4.5 ± 3.9

Interestingly, significance mean difference was found in one criterion in the soccer sport group only. There was a statistically significant difference PT of knee flexion @ 60°/s between groups as determined by one-way ANOVA (F (3, 61) = 2.861, p = 0.044). Furthermore, a LSD post-hoc test (Table 5.4) revealed that cut-off percentages of rugby athletes' group was significantly lower (9.7 ± 6.8 Nm, p = 0.013) and the same goes to the track and field athletes' group (7.3 ± 6.3 Nm, p = 0.021) when compared to the soccer athletes group (17.5 ± 15.4 Nm). There were no statistically significance difference between soccer and cricket athletes' groups (p = 0.161).

Table 5.4: Identifying the sport groups with significance difference in threshold% on Knee Flex 'strength' @ 60°/s criterion. Significance values were highlighted with (*).

One-way ANOVA / POSTHOC=LSD ALPHA (0.05).					
Dependent Variable	**Sport**		**Mean Difference**	**Std. Error**	**Sig.**
Knee Flex @ 60°/s 'strength'	SOCCER	CRICKET	5.4722	3.8556	0.161
		RUGBY	7.7817	3.0473	0.013*
		ATHLETIC	10.1632	4.2890	0.021*

Furthermore, the threshold percentages of all criteria were shown in Table 5.5. These thresholds data were produced by applying Equation 2 [Threshold % = mean of AAV% + SD] on all the generated absolute asymmetry values found in Table 5.3. This procedure was essential to be implemented to determine exact threshold percentage to each criterion rather than testifying a misread percentage by quantifying the amount of dispersion within mean and SD as argued previously (section 3.3.1).

Since the thresholds were single values, a further descriptive analysis based on the threshold boundary was conducted to examine the eccentric threshold values between sport groups in each criterion. The threshold boundary is the values between the sums of mean ± SD of all sport groups' thresholds within a criterion. Threshold values found below the boundary will be highlighted as (-) and, greater values will be highlighted with (+). For example, the average and standard deviation of LLD's thresholds was 1.03 ± 0.17; thus, the boundary range between the four groups falls between 1.2-0.9 (i.e. 1.03 + 0.17 = 1.2 and 1.03 – 0.17 = 0.9); Therefore, Cricketer diagnosed with (-) since 0.8 ≤ 0.85, whereas rugby diagnosed with (+) as their threshold was ≥ 1.2 (Table 5.5).

Table 5.5: The threshold percentages of all criteria within each sport-specific group of athletes. Descriptive analysis test based on threshold boundary was executed between sport groups. Values outside the boundary were highlighted with (-) if ≤; with (+) if ≥ calculated boundary (n= 79).

Criteria	*Threshold %*				Boundary Range
	Cricket	Rugby	Soccer	Athletic	
Ankle DF 'flexibility'	**- 8.1**	14.5	14.8	17.8	17.9 - 9.7
Quads 'flexibility'	12.3	11.9	**- 8.6**	9.9	12.4 - 8.9
Hams 'flexibility'	**- 22.5**	31.3	29.6	**+ 38.1**	36.8 - 24.0
LLD	**- 0.8**	**+ 1.2**	1.1	1.0	1.2 - 0.9
TCD	4.3	3.3	3.9	**- 2.3**	4.3 - 2.6
CCD	2.8	**+ 3.0**	2.6	**- 2.3**	3.0 - 2.4
Knee Ext @ 60°/s 'strength'	**+ 24.9**	15.0	15.4	13.1	22.4 - 11.8
Knee Flex @ 60°/s 'strength'	19.5	16.5	**+ 32.9**	13.6	29.2 - 12.1
1LH	**+ 17.9**	11.5	9.8	**- 4.7**	16.4 - 5.5
1LTH	**+ 13.3**	5.8	6.3	3.9	11.4 - 3.2
1LCMJ Height	21.8	14.4	21.8	N/T	N/T
1LCMJ Max Force	7.8	9.5	9.0	N/T	N/T
StdBWD	9.1	10.8	11.4	**- 7.1**	11.5 - 7.7
CMJ Max Force	9.3	8.5	**- 5.0**	8.0	9.6 - 5.8
CMJ Avg Ecc Force	13.0	12.8	**- 10.2**	12.0	13.3 - 10.7
CMJ Avg Con Force	10.2	10.0	**- 4.4**	8.4	10.9 - 5.6

5.4 Discussion

The same methodological statistical analysis approach was executed in Chapter four to investigate bilateral asymmetry. This approach discloses AAV percentages for key criteria selected from four different attributes (anthropometric, strength, flexibility and functional ability) in the lower limbs based on absolute asymmetry difference between lower limbs for elite-athletes.

Various lower limb characteristics were measured to examine BA. Therefore, normative data in the form of AAV percentages for different lower-limb criteria were established in order to generate their threshold boundary percentages. Consequently, these threshold percentages enabled for further statistical analysis by comparing the attributes between sport groups using the one-way ANOVA test. Interestingly, there were no statistically significant finding between attributes when all sport groups were tested and that does not support the assumption of, when an athlete involves professionally in a certain kind of sport he or she may develop a distinguished anthropometric or/and flexibility or/and strength characteristics which can be developed throughout the years by professionally practicing that specific sport. The assumption was based on that each sport has it is own unique kinetics and kinematics properties (Table 5.5). However, interesting findings were revealed from the data when the one-way ANOVA test was executed in order to compare the mean of every single criterion across sport groups. The BA threshold percentage of the PT in knee flexion @ 60°/s for soccer athletes' group manifest a significant threshold percentage mean difference when compared with rugby and athletic sport groups. This indicates that there is a significant influence on elite-athletes in term of developing BA on their knees' flexor muscle groups when they are professionally competing in soccer at some point during their career. When comparing the soccer elite-athletes group (n= 19) descriptively, 17 athletes (89%) reported that their dominant leg is the right and, when examining them statistically it was found that; 6 (35%) athletes have stronger left knee's flexor muscle, 9 (53%) athletes have stronger right knee's flexor muscle and, 2 (12%) athletes were exactly balanced. Concomitantly, a paired-samples t-test was conducted to compare the peak torque (Nm) of both knee flexors. There was no significant difference in the mean ± SD of right leg score (85.5 ± 41.7) and the left one (81.3 ± 45) conditions; $t(18) = 1.143$, $p = 0.268$. These results suggest that no significant difference between the means of all right legs when compared with the left ones which is agreed with previous researches (Hvid et al., 1981; Beckett et al., 1992; Astrom and Arvidson, 1995; Sobel et al., 1999; Newton et al., 2006) that been introduced earlier in the literature (Section 2.7). Specifically, the results based on of the descriptive analysis suggest that having a preferred leg to stand on during landing is not an indication to have a stronger knee's flexor group and that disagreeing with the assumption of having a stronger knee's flexor muscle group. Remarkably, LLD scored the lowest threshold percentages across all elite-athlete groups (Table 5.5). This key finding is an indicator for not looking to the entire examined attributes at the same level of percentage as argued previously in the literature (Section 2.5).

Interestingly, the criterion with the highest threshold found in Table 5.5 was the hamstring flexibility by scoring 38.1% whereas the lowest one was 0.8% and scored by the cricketers when measuring their LLD. However, the one-way ANOVA test did not pick up undeniable differences between sport groups for a number of criteria (13.3 and 3.9 in 1LTH). Such variance, was able to be identified only by utilising the threshold boundary test.

Furthermore, when examining threshold percentages across all sport groups (Tables 5.5) many interesting findings can be addressed based on the causative factors of bilateral asymmetry (Figure 1.1). It was noticed in general that, track and field athletes were the least asymmetric among the other sport groups in all attributes (Anthropometric, isokinetic, NFPT and CMJ) except for the flexibility. Such superiority, could be as a result from being closely supervised by their rehabilitation team since they are competing in individual kind of sports (Single and triple jumpers). As per their strength profile, it is suggested that the elite track and field superior symmetry of their quadriceps and hamstrings is due to the urge to perform with maximum intensity in both legs as they need to alter between them when competing without showing lack of difference between lower limbs.

This study has showed also that soccer players have a very high BA level across all sport groups. Such increased asymmetry could be due to the individual preference of standing when stabilising one leg in order to kick with the other, as repeating this pivoting manoeuvre strengthen the hamstrings muscle eccentrically. On the other hand, for the opposite muscle group (knee extension at 60°/s); cricketers had the highest BA threshold percentage when compared with the rest of the other groups. Although this variance is not significant, no exact explanation can be given except for the fact that competing in cricket requires constant changing directions and that means accelerating and decelerating consistently. However, in order to answer such speculation, a further investigation can be focused on the athlete’s kinematics and kinetics when competing in a simulated game and that would allow understanding whether or not athletes prefer stressing a leg over the other especially when the game is played as a group and not as individual as per different positions necessitates unique movements. Nevertheless, such differences in performance between lower limbs is not necessarily a wicked or preferable phenomenon, as some techniques (For example, kicking the ball in a free kick on a soccer match) require repeated training on one leg over the other which consequently may develop some level of blessed bilateral asymmetry profile in athletes.

When examining the threshold percentages between sport groups for all criteria, many interesting finding were discovered. In term of strength imbalance, elite rugby athletes manifested by far, the highest peak torques at 60°/s in both tested muscle groups (extension and flexion). In accordance to the flexibility of the joints, elite cricketers were the most symmetric group in term of their joint flexibility as they have manifested the lowest threshold percentages in two out of three criteria (ankle's dorsiflexion and hamstrings flexibility). Lastly, the group of elite rugby athletes was the most symmetric group in the anthropometric discrepancies measurements as they have cored the lowest threshold percentages when compared with the rest of the groups (Table 5.5). Furthermore, as it would be expected when testing the neuro functional performance tests, the elite track and field athletes topped both tests (1LH and 1LTH) as they have scored the lowest threshold percentages in both tests when compared with the rest of the groups.

Additionally, when looking at the body weight two-legged countermovement jump height, no study has looked into comparing the performances of CMJ across different group of athletes. For example, when comparing the average height of CMJ across athlete's groups as track and field athletes jumped the highest among the other groups followed closely by soccer players 0.357 ± 0.041 and 0.351 ± 0.060 m respectively. In contrary, cricketers scored the lowest average CMJ height. Another example is, this study showed in term of force production during CMJ that, rugby athletes group scored the highest average force in all the measured criteria of the CMJ attribute.

Finally, this study has several advantages. Firstly, it has suggested to following the generated sport-specific norms that could help the athletes during their rehabilitation process. Secondly, such norms could be utilised as a benchmark, since this study has established a very large number of focused norms and, sport clubs do not tend to share such specific knowledge. Thirdly, it introduced a descriptive statistical analysis approach to compare a single value (Threshold percentage only) between groups using the threshold boundary. This novel approach has identified eccentric values between sport groups that could not be executed with other kind of statistical analysis tests. Lastly, it may aid in raising the standards of rehabilitation services by implementing a more objective assessment's tool when diagnosing BA.

5.5 Conclusion

This study has utilised the same bilateral asymmetry analysis bundle introduced earlier in Chapter 4. However, it methodology was constructed differently in order to answer different question of the research's thesis (Section 1.1). This study has investigated BA in lower limbs in a more specific groups of athletes. In conclusion, this study could serve a great number of high-end rehabilitation sport teams in term of diagnosing sport specific elite-athletes with bilateral asymmetries in lower limbs. The established threshold percentages could be applied as a professional assessment tool utilised by practitioners and researchers. Such norms, could determine objectively and accurately, when to interfere after assessing elite-athletes for their readiness for intense competition. Another advantage of this assessment tool is, it can be used during the pre-season screening to stand on the athletes' physical conditions or during mid-season to monitor their training progress.

This novel study had also suggested carrying out the same descriptive statistical analysis approach (creating boundary to identify eccentric values) when comparing different groups based on single value. Apparently, executing the one-way ANOVA with LSD post-hoc test between the mean threshold percentages of each criterion across all sport groups displayed more understanding over examining the differences across the groups based on the attributes. Consequently, this study has showed that the high BA in the knee's flexor of soccer elite-athletes differs significantly from rugby and track and field athletes which could suggests further studies for better understating how soccer has an influence on the elite-athletes in this particular criterion.

A good example of how these unique kinetics and kinematics properties express themselves during performance was, the average strength of rugby elite-athletes, as it was the highest among other groups. Such high values could be due to the continuous physical demand as it requires a lot of contact with the opponent with great force to push them in order to cut through defences. Another example of linking the threshold to the performance was found in track and field athletes as they highly focused their training programme to strengthen their thigh and calf muscles in order to jump as far as they could which can be seen when compared with the soccer player (Since average age is similar) as seen in Table 5.2.

Lastly, some researchers have speculated about the sufficient number of tests required to investigate a proper examination to assess bilateral asymmetry in the lower limbs (Theoharopoulos et al., 2000; Rahnama et al., 2005; Newton et al., 2006; Impellizzeri et al., 2007; Croisier et al., 2008) however, this study has managed to recruit the most related key criteria in lower limbs that may affect athletes' functional tasks (countermovement jump and running gait). Indeed, as it is not always right to go with say the more the better or size does matter in term of sample size. Therefore, standardising or having an exact sample size for all tested groups depends on the team's compliance and exclusivity of the team. Nevertheless, gaps between training schedules could played a major role in causing such variance. Another key factor is the considerations that needs to bear in mind when deciding the feasibility of tested criteria. For example, it would be recommended to add electromyography device when performing isokinetic testing however, doing so would reduce the sample size dramatically, as including this procedure within the testing protocol would takes an extra thirty to forty-five minutes per participant to fulfil the whole battery of testing.

After setting the threshold percentages of key criteria in lower limbs, Chapter 6 has inspected the asymmetry agreement between criteria that associated with the criteria of countermovement jump (concentric average force, eccentric average force and maximum force). The variance of bilateral asymmetry during countermovement jump is believed to accountable to the asymmetry generated in key criteria in lower limbs. Therefore, every criterion of CMJ will be running a number of statistical analysis tests to examine the relationship between it a long with key criteria in lower limbs.

6.0 STUDY THREE

Title: Agreement between attributes associated with bilateral jump asymmetry

6.1 Introduction

Bilateral asymmetry in lower limbs is an important field of which rehabilitation sport teams look into when evaluating athletes for dis-capabilities. However, the interpretation into examined data was vastly inconsistent among practitioners (Barber et al., 1990; Noyes et al., 1991; Anderson et al., 1991; Swarup et al., 1992; Barber et al., 1992; Wilk et al., 1994; Greenberger and Paterno, 1995; Wilson and Murphy, 1995; Petschnig et al., 1998; Ostenberg et al., 1998; Augustsson and Thomee, 2000; Kovaleski et al., 2001; Tomioka et al., 2001; Baker et al., 2001; Ugarkovic et al., 2002; Ross et al., 2002; Tsiokanos et al., 2002; Keays et al., 2003; Newton et al., 2006; Impellizeri et al., 2007). Thus, it is believed that findings are somewhat dependent upon the way data is collected and analysed. This is especially true when attempting to review the literature for bilateral asymmetry, which lacks consistency. This is largely due to differences in the methodologies used, whether researchers have studied the dominant/non-dominant, preferred/non-preferred, right/left, or strongest/weakest limbs, and how researchers have defined dominant or preferred leg as well as type of tested populations (Section 2.7).

When clinicians investigate compensatory movements in athletes during movements they tend to examine any bilateral asymmetry in their performance as asymmetry may develop throughout the season if it is not being monitored. Such developed asymmetry in athletes may hinder their unique kinematic characteristics during competition or could lead them to risk of injury (Klein, 1970; Knapik et al., 1991; Yamamoto, 1993; Orchard et al., 1997; Arendt and Griffin, 2000; Hewett et al., 2001; Soderman et al., 2001; Tyler et al., 2001; Croisier et al., 2002; Newton et al. 2006; Paterno et al., 2007; Fousekis et al., 2010). Indeed, many sports skills require athletes to repeat certain movements quite often unilaterally and that could be during competitions as well as training in order to reach certain enhanced level of performance. On the other hand, repetition over time for some certain asymmetrical activities, may lead to distinctive beneficial loading patterns on joints and muscles which the body adopt consequently and utilised as an advantage. The same principle of bilateral asymmetry differences apparent itself in bilateral exercises as coordinating specific movements (for example, CMJ) could consequently lead to injuries however such speculations still remains inconclusive.

There were several limitations to previous research examining bilateral countermovement jump asymmetry. Most researchers focussed their investigations on the association between individual factors only. Such approach, has limited examining the influence of key criteria in lower limbs into the CMJ's criteria itself or other functional ability. For example, strength and jump asymmetry (Impellizzeri et al., 2007; Newton et al., 2006). There has been no holistic examination approach that examined multiple factors which may be associated with jumping asymmetry (i.e. strength, anthropometric differences, range of motion or flexibility). Additionally, the use of correlations may not be the most appropriate choice of analysis, as it has compared the associations in the magnitude of asymmetry only. In clinical scenarios, it is more meaningful to classify whether athletes are diagnosed for being bilaterally asymmetrical or not as this would determine where to focus their plan of care by the rehabilitation team on them. Thereby, every measurement would need a specific threshold and, that is the key for which an asymmetry has be classified. Previous studies has suggested arbitrary thresholds of 10% (Schiltz et al., 2009) to 15% (Bennell et al., 1998; Croisier et al., 2002), however these thresholds are believed be inappropriate for all criteria measurements such as leg length discrepancy, where differences of 10% were extremely unlikely to be seen in elite athletes. Thus, to understand the real association between factors, it would be more interesting to examine the level of agreements between the diagnoses of bilateral asymmetry between key factors.

Lastly, this study has two aims. Firstly, to establish thresholds for key criteria in the lower limbs in order to, determine the level of agreements between CMJ's criteria along with strength, anthropometric, flexibility and single leg jump criteria. Whereas the other one is, to investigate any effect on the force platform profile (Figure 3.4) when manipulating leg length discrepancies across different sets of CMJ trials.

6.2 Methodology

To achieve the aims of this study the methodology was split into two experiments. The first was, a retrospective study based on data collected from colligate and elite-athletes of the previous two studies (study 1 and 2). A total of one hundred and forty-four subjects were selected from a diverse range of sports (123 males, 21 females). The mean ± SD age, height and mass of the participants were 22 ± 5 years, 177.9 ± 9.4 cm, and 80.0 ± 16.6 Kg respectively. The level of activity in the population was mixed as seventy-three subjects were elite and seventy-two were colligate athletes. The screening battery of testing involved tests and measurements for a number of sub-categorised criteria that form key attributes in order to diagnose BA in the lower limbs as explained previously (Section 4.2). However, only three criteria were used from each attribute to execute the designated analysis of this study.

The selected CMJ force variables from the left and right limbs were the maximum force and the average forces in both eccentric and concentric phases. The aforementioned measurements were automatically extracted from a consumedly designed software that has been mentioned earlier in Section 3.3.4.

The bilateral asymmetry threshold percentage was calculated from the mean absolute difference ±SD that found between lower limbs [Equation 2; Section 3.3.1]. If one or more of the three criteria exceeded the threshold, then that attribute was deemed asymmetrical. The overall level of asymmetry agreement in diagnoses between the criteria of countermovement jumps and key criteria in lower limbs were examined by counting the frequency and percentage of like for like diagnoses of asymmetry, i.e. either both asymmetrical or balanced using [Equation 3; Section 3.3.1].

A qualitative measurement of agreement was used based on the absolute mean difference criteria. This required, for example, if the diagnosis between variables was the same, (i.e. symmetrical = symmetrical; asymmetrical = asymmetrical) then this was given a value of 1. For contrasting diagnoses, a value of 0 was given. The percentage "agreement" was then determined by the sum of all the individual agreements expressed as a percentage of the number of subjects [Equation 3; Section 3.3.1].

The secondary aspect of this study was to examine the effect of artificially rectifying the force distribution profile by changing the level of floor beneath the two feet. This would have the same effect on the level of the hips as would a leg length discrepancy. A sub-group of 10 participants from the main study performed a few additional bilateral CMJ tests in scenarios where the force platforms were levelled and when the surface was raised by 0.8cm and 1.6cm on both sides independently. Due to the novelty of this experiment, the decision of choosing these heights was solely based on the researcher's clinical judgment. Such discrepancy in the aforementioned heights were believed to be affecting athletes' function and this decision has also supported by a number of studies (Gurney, 2002; Brady et al., 2012; AAOS.org, 2016). Therefore, a height of 0.8cm was integrated to the athletes into one side of the lower limbs. Such height can be also corrected for subjects with actual leg length discrepancy by clinicians without surgical intervention even if the height was doubling that. The mean age, height and mass of the subjects were 33 ± 3.2 years, 173 ± 7.7 cm and 83 ± 14 Kg respectively. The sequence of the counter movement jump sets was as follow; the participants were asked to stand still on an adjacent and levelled force plates (each leg on a force platform) then to perform a set of CMJ, then, an aluminium plate with a height of 0.8 cm was placed under the right force platform to elevate the right force platform by 0.8 cm, after which the athletes performed a set of three CMJ. After that, the left hand force platform was raised by 0.8 cm and athletes performed a further 3 CMJ's. The surface was then raised to 1.6 cm to double the difference in surface level and jumps were again performed with the right and left force platforms in the elevated position. In total 15 CMJ's were performed.

All data were analysed as previously described and, the effect on load distribution and the diagnosis of asymmetries was quantified.

6.3 Results

The first part of the results section has examined descriptively the association between variables based on asymmetry agreement test. The statistical analysis comparison between all variables was based on a recalculated threshold percentages generated for this specific retrospective study (mixed-athletes) and, the generated threshold can be seen in Table 6.1.

Table 6.1: Threshold % (cut-off) of mixed-athlete's group (n=144).

Criteria	Threshold %
Ankle DF 'Flexibility'	13.7
MTT 'Flexibility'	10.5
AKE Test 'Flexibility'	27.7
LLD	1.1
TCD	3.6
CCD	3.3
Q @ 60°/s 'strength'	18.2
H @ 60°/s 'strength'	22
1LH	14.6
1LTH	11.9
1LCMJ Height	18.8
1LCMJ Max Force	9.2
StdBWD Force	12.1
CMJ Max Force	9.8
CMJ Avg Ecc Force	14
CMJ Avg Con Force	10.8
Abbreviations; DF= Dorsiflexion; Q @ 60°/s 'strength'= Testing the isokinetic peak torque of quadriceps muscle at 60°/s; H @ 60°/s 'strength'= Testing the isokinetic peak torque of hamstrings muscle at 60°/s, 1LH= One-legged hop, 1LTH= one-legged triple hop, lLCMJ Max Force= Maximum force of one-legged countermovement jump, , CMJ= countermovement jump, Avg Ecc Force= Average eccentric force, Avg Con Force= Average concentric force, MMT= Modified Thomas test, AKE= Active Knee Extension, LLD= Leg length discrepancy, TCD= Thigh circumference discrepancy, CCD= Calf circumference discrepancy, StdBWD= Standing body weight distribution.	

The percentage of agreement between one to another variable was produced based on the frequency of like-like agreement found between variables of countermovement jump along with key variables in the lower limbs and, divided by the actual number of tested subjects in that specific analysis (Tables 6.2-4). The methodology of diagnosing participants for being symmetric or not in each variable was introduced in Section 6.2.

Furthermore, an additional analysis was executed to examine the association between two variables using the Pearson's correlation in two sets of data; the first correlation was calculated based on the absolute asymmetry value percentages generated for all variables whereas, the other one; based on the actual asymmetry value (not the absolute) percentage of each criterion (Tables 6.2-11). The Pearson's correlation test was utilised by Newton et al., (2006) to report any significant correlation between two variables. Therefore, it was administered in this study's methodology to provide a further insight into how the proposed approach of 'asymmetry agreement' statistical analysis differ from Newton's approach. In order for any of the Pearson's results to be significantly correlated, it has to reach or exceeds a critical value which changes based on the number of comparisons/participants. Pearson correlation's critical values were obtained from Fort Lewis Collage's website (fortlewis.edu, 2015). The significance was set at $p = 0.05$.

Table 6.2: Comparisons between CMJ Max Force (All Data) and related key variables using the association of asymmetry agreement % and, Pearson's r correlation tests. The r correlation was set for significance at 0.05. Critical values were highlighted with (*))

Variable 1	Variable 2	No. of Comparison	No. of Agreement	Agreement %	Correlation Abs, r =	Correlation r =
CMJ Max Force	StdBWD	144	117	81.3	0.155	-0.122
CMJ Max Force	CMJ Avg Ecc Force	144	117	81.3	0.281*	-0.052
CMJ Max Force	CMJ Avg Con Force	144	125	86.8	0.721*	-0.293
CMJ Max Force	LLD	144	110	76.4	0.055	0.026
CMJ Max Force	TCD	144	120	83.3	0.090	0.045
CMJ Max Force	CCD	144	119	82.6	0.074	-0.133
CMJ Max Force	Q @ 60°/s 'strength'	118	91	77.1	0.039	-0.237
CMJ Max Force	H @ 60°/s 'strength'	118	94	79.7	0.189*	-0.169
CMJ Max Force	1LH	106	92	86.8	0.318*	0.019
CMJ Max Force	1LTH	106	94	88.7	0.274*	0.040
CMJ Max Force	1LCMJ Height	88	68	77.3	0.197*	-0.374
CMJ Max Force	1LCMJ Max Force	88	71	80.7	0.107	-0.085

Table 6.3: Comparisons between CMJ Avg Ecc Force (All Data) and related key variables using the association of asymmetry agreement % and, Pearson's r correlation tests. The r correlation was set for significance at 0.05. Critical values were highlighted with (*))

Variable 1	Variable 2	No. of Comparison	No. of Agreement	Agreement %	Correlation Abs, r =	Correlation r =
CMJ Avg Ecc Force	StdBWD	144	120	83.3	0.573*	0.738*
CMJ Avg Ecc Force	CMJ Avg Con Force	144	114	79.2	0.172*	0.304*
CMJ Avg Ecc Force	LLD	144	109	75.7	-0.067	-0.010
CMJ Avg Ecc Force	TCD	144	113	78.5	0.125	0.140
CMJ Avg Ecc Force	CCD	144	114	79.2	-0.074	0.032
CMJ Avg Ecc Force	Q @ 60°/s 'strength'	118	87	73.7	-0.122	0.090
CMJ Avg Ecc Force	H @ 60°/s 'strength'	118	90	76.3	-0.057	0.001
CMJ Avg Ecc Force	1LH	106	82	77.4	0.029	0.140
CMJ Avg Ecc Force	1LTH	106	86	81.1	0.001	0.127
CMJ Avg Ecc Force	1LCMJ Height	88	68	77.3	0.008	0.132
CMJ Avg Ecc Force	1LCMJ Max Force	88	69	78.4	0.081	0.036

Table 6.4: Comparisons between CMJ Avg Con Force (All Data) and related key variables using the association of asymmetry agreement % and, Pearson's r correlation tests. The r correlation was set for significance at 0.05. Critical values were highlighted with (*))

Variable 1	Variable 2	No. of Comparison	No. of Agreement	Agreement %	Correlation Abs, r =	Correlation r =
CMJ Avg Con Force	StdBWD	144	112	77.8	0.058	0.078
CMJ Avg Con Force	LLD	144	117	81.3	0.059	0.015
CMJ Avg Con Force	TCD	144	119	82.6	0.117	0.082
CMJ Avg Con Force	CCD	144	118	81.9	0.068	0.127
CMJ Avg Con Force	Q @ 60°/s 'strength'	118	96	81.4	0.251*	0.404*
CMJ Avg Con Force	H @ 60°/s 'strength'	118	93	78.8	0.192*	0.249*
CMJ Avg Con Force	1LH	106	91	85.8	0.332*	0.339*
CMJ Avg Con Force	1LTH	106	93	87.7	0.257*	0.345*
CMJ Avg Con Force	1LCMJ Height	88	69	78.4	0.236*	0.487*
CMJ Avg Con Force	1LCMJ Max Force	88	70	79.5	0.169*	0.107

The associations found in Tables 6.2-4 were based on a population with subjects having bilateral asymmetry in the standing with their body weight only, which may not provide a holistic understanding on the influence of key variables on the variables of countermovement jumps. Thus, a further analysis was conducted based on the same associations, however, this time on the same population without the athletes who have bilateral asymmetry in their standing weight distribution variables (Tables 6.5-7). The aim of this subsequent analysis was to examine how the asymmetry agreement test associations may differ from one to another without the effect of standing with bilateral asymmetry in weight distribution.

Table 6.5: Comparisons between CMJ Max Force (All Data without a StdBWD Asymmetry) and related key variables using the association of asymmetry agreement % and, Pearson's r correlation tests. The r correlation was set for significance at 0.05. Critical values were highlighted with (*))

Variable 1	Variable 2	No. of Comparison	No. of Agreement	Agreement %	Correlation Abs, r =	Correlation r =
CMJ Max Force	StdBWD	124	95	76.6	0.062	-0.075
CMJ Max Force	CMJ Avg Ecc Force	124	102	82.3	0.250*	-0.049
CMJ Max Force	CMJ Avg Con Force	124	111	89.5	0.719*	-0.401
CMJ Max Force	LLD	124	99	79.8	0.059	0.028
CMJ Max Force	TCD	124	105	84.7	0.090	0.092
CMJ Max Force	CCD	124	103	83.1	0.030	-0.214
CMJ Max Force	Q @ 60°/s 'strength'	103	80	77.7	0.109	-0.279
CMJ Max Force	H @ 60°/s 'strength'	103	83	80.6	0.209*	-0.224
CMJ Max Force	1LH	90	82	91.1	0.325*	-0.064
CMJ Max Force	1LTH	90	80	88.9	0.262*	0.019
CMJ Max Force	1LCMJ Height	78	62	79.5	0.221*	-0.360
CMJ Max Force	1LCMJ Peak Force	78	61	78.2	0.091	-0.010

Table 6.6: Comparisons between CMJ Avg Ecc Force (All Data without a StdBWD Asymmetry) and related key variables using the association of asymmetry agreement % and, Pearson's r correlation tests. The r correlation was set for significance at 0.05. Critical values were highlighted with (*))

Variable 1	Variable 2	No. of Comparison	No. of Agreement	Agreement %	Correlation Abs, r =	Correlation r =
CMJ Avg Ecc Force	StdBWD	124	95	76.6	0.391*	0.639*
CMJ Avg Ecc Force	CMJ Avg Con Force	124	99	79.8	0.143	0.370*
CMJ Avg Ecc Force	LLD	124	97	78.2	-0.067	-0.077
CMJ Avg Ecc Force	TCD	124	101	81.5	0.082	0.154
CMJ Avg Ecc Force	CCD	124	101	81.5	-0.041	0.128
CMJ Avg Ecc Force	Q @ 60°/s 'strength'	103	77	74.8	-0.060	0.111
CMJ Avg Ecc Force	H @ 60°/s 'strength'	103	80	77.7	-0.030	0.052
CMJ Avg Ecc Force	1LH	90	75	83.3	0.003	0.158
CMJ Avg Ecc Force	1LTH	90	75	83.3	-0.009	0.219*
CMJ Avg Ecc Force	1LCMJ Height	78	60	76.9	-0.010	0.135
CMJ Avg Ecc Force	1LCMJ Peak Force	78	59	75.6	-0.053	0.086

Table 6.7: Comparisons between CMJ Avg Con Force (All Data without a StdBWD Asymmetry) and related key variables using the association of asymmetry agreement % and, Pearson's r correlation tests. The r correlation was set for significance at 0.05. Critical values were highlighted with (*))

Variable 1	Variable 2	No. of Comparison	No. of Agreement	Agreement %	Correlation Abs, r =	Correlation r =
CMJ Avg Con Force	StdBWD	124	92	74.2	-0.049	0.144
CMJ Avg Con Force	LLD	124	102	82.3	0.057	0.038
CMJ Avg Con Force	TCD	124	104	83.9	0.081	0.162
CMJ Avg Con Force	CCD	124	100	80.6	0.045	0.176*
CMJ Avg Con Force	Q @ 60°/s 'strength'	103	84	81.6	0.300*	0.449*
CMJ Avg Con Force	H @ 60°/s 'strength'	103	81	78.6	0.207*	0.252*
CMJ Avg Con Force	1LH	90	81	90.0	0.350*	0.371*
CMJ Avg Con Force	1LTH	90	81	90.0	0.261*	0.354*
CMJ Avg Con Force	1LCMJ Height	78	66	84.6	0.235*	0.486*
CMJ Avg Con Force	1LCMJ Peak Force	78	61	78.2	0.089	-0.026

Table 6.8: Comparisons between key variables using the association of asymmetry agreement % and, Pearson's r correlation tests. The r correlation was set for significance at 0.05. Critical values were highlighted with (*))

Variable 1	Variable 2	No. of Comparison	No. of Agreement	Agreement %	Correlation Abs, r =	Correlation r =
All Data						
StdBWD	LLD	144	113	78.5	-0.050	-0.007
TCD	Q @ 60°/s 'strength'	118	86	72.9	-0.120	-0.003
TCD	H @ 60°/s 'strength'	118	89	75.4	-0.067	-0.081
1 LCMJ Peak Force	1LH	68	55	80.9	0.143	0.115
1LCMJ Peak Force	1LTH	68	57	83.8	0.061	0.109
1LCMJ Height	1LH	68	54	79.4	0.469*	0.120
1LCMJ Height	1LTH	68	58	85.3	0.378*	0.429*
All Data without a StdBWD Asymmetry						
StdBWD	LLD	124	90	72.6	-0.079	-0.111
TCD	Q @ 60°/s 'strength'	103	75	72.8	-0.116	-0.025
TCD	H @ 60°/s 'strength'	103	78	75.7	-0.053	-0.041
1LCMJ Peak Force	1LH	60	47	78.3	0.066	-0.007
1LCMJ Peak Force	1LTH	60	50	83.3	0.081	0.077
1LCMJ Height	1LH	60	51	85.0	0.468*	0.073
1LCMJ Height	1LTH	60	54	90.0	0.428*	0.440*

Similar associations were found when comparing the results of asymmetry agreement percentages from Tables 6.2-4 with the ones in Tables 6.5-7, this suggests that it is applicable to compare CMJ's variables with other variables to examine the asymmetry agreement between them in a general population (with ones whom have already asymmetry in their body weight distribution when standing still).

Interestingly, at least three out of four participants (All association ≥ 73.7 %) agreed to have the same diagnosis (symmetric or asymmetric) between any comparison of two variables (Tables 6.2-8). This means, for example, in Table 6.2, when examining the association between the criteria of "CMJ Max Force" and "LLD" it was found that, out of the 144 participants, 110 athletes agreed to have the same diagnosis in both variables (either not exceeding threshold in both criteria and classified as symmetric or exceeding the threshold in both tests and doomed to be asymmetric). In fact, in some comparisons, the percentage of agreements has reached up to 88.7% (CMJ Max Force – 1LTH) which means in clinical relevance, that for every four out of five participants agreed to have the same diagnosis in that specific association (balanced = balanced or asymmetric = asymmetric). Nevertheless, the majority of agreement's percentages have fallen between 75% (3 out of 4 participants) and 80% (4 out of 5 participants). Furthermore, when examining the subsequent populations (With or without having an asymmetry in their body weight while standing still), there were still high level of agreements between variables except for the CMJ's criteria with isokinetic tests in both population and flexibility of gastrocnemius/soleus and quadriceps muscles in the population that has an asymmetry in their body weight while standing still as these associations showed no agreement between these specific variables.

As for the second experiment in this study, the results showed some instant beneficial outcomes on the CMJ variables after manipulating the leg length in certain trials. The threshold percentages generated in the main study were utilised to diagnosed BA for the performance of this specific group (Table 4.5). Thereby, the results presented in Table 6.9 have showed the percentage of population whom exceeded the BA thresholds in all criteria. Interestingly, half of the population has exceeded the threshold percentage in LLD criterion.

Table 6.9: The existed percentages of population for whom exceeded the threshold percentages within each criterion (n=10)

Criteria	ID No. of subjects diagnosed with BA	Population's percentage with existed BA (%)
Ankle DF 'flexibility'	2, 10	20
Quads 'flexibility'	Nil	0
Hams 'flexibility'	Nil	0
LLD	1, 4, 6, 7, 9	50
TCD	2, 3	20
CCD	3, 9	20
Quads 'strength'	Nil	0
Hams 'strength'	Nil	0
1LH	3	10
1LTH	3	10

When examining the CMJ criteria (the focus of this study) it was found that, 20% of the tested population exceeded the threshold of at least one of the CMJ criteria during the levelled CMJ set (Table 6.10). More specifically, two subjects exceeded the BA cut-off percentage of BW distribution on the levelled platforms in the standing body weight distribution (StdBWD) force and, one of them has also, diagnosed with BA in the concentric average force criteria. Remarkably, the percentage of population whom had BA in at least one of the CMJ criteria has jumped from being 20 to be 90% (Figure 6.1) after raising the force platform by 0.8 cm on either leg (all subjects except participant no.7) and, the same result was found when the 1.6 cm plate was added to either leg (all subjects except participant no.4).

Table 6.10: BA percentages existence comparison across all CMJ sets based on the population percentages of subjects whom exceeded the threshold percentages of CMJ criteria (A = StdBWD, B = Max force, C = Ecc Avg force, D = Con Avg force and £ = Symmetrical).

Subject ID	Bilateral Asymmetry Existence				
	Levelled	R +0.8 cm	L +0.8 cm	R +1.6 cm	L +1.6 cm
1	£	A	£	£	A, C, D
2	A	B, D	B, C, D	D	B, C, D
3	A, D	B, D	£	B, D	A, C, D
4	£	£	A	£	£
5	£	A	C	£	C
6	£	C	£	A, C	A
7	£	£	£	£	A
8	£	£	A	C	C
9	£	£	A, C	A	£
10	£	£	C	C	A, C
Population %	20	50	60	60	80

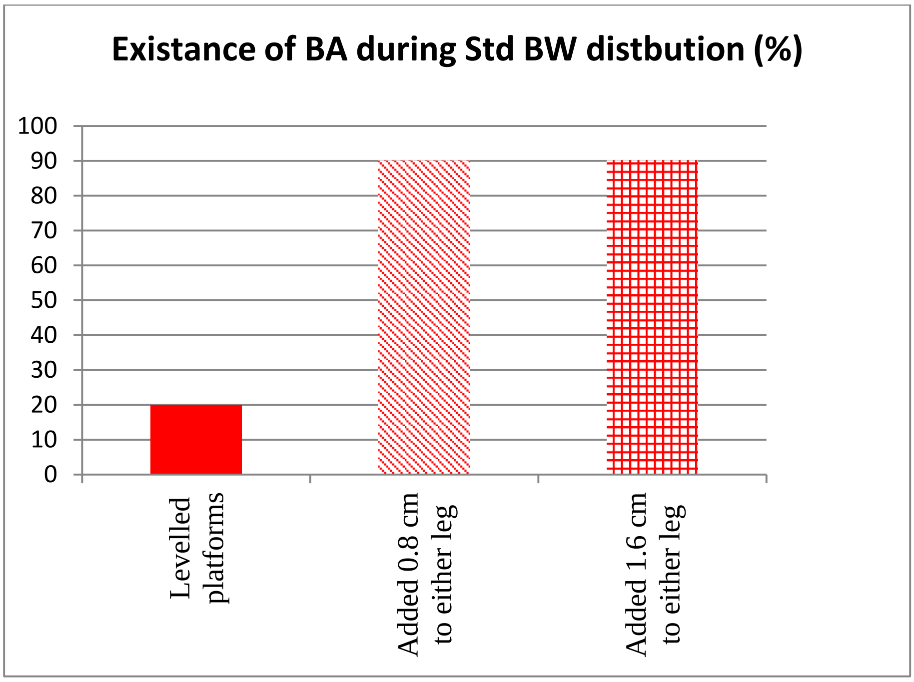

Figure 6.1: Percentage of population whom had BA in at least one of the CMJ criteria on levelled force platforms and, after adding 0.8 and 1.6 cm plate to either side of the force platform (n=10)

Additionally, Table 6.11 has compared all CMJ criteria across all the five sets with the LLD criteria in term of BA existence by highlighting all the tests that exceeded the threshold percentages of each criterion.

Table 6.11: BA (%) existence comparison of CMJ criteria across all jump sets (Levelled platforms, + 0.8 cm on R side, + 0.8 cm on L side, + 1.6 cm on R side and + 1.6 cm on L side) with LLD criterion (Exceeded BA% were highlighted with (*)).

Sub ID	Test	StdBWD Force		Max Force		Avg Ecc Force		Avg Con Force		LLD
	raised side	R	L	R	L	R	L	R	L	
	Levelled	7.3		3.1		3.2		3.9		
1	+ 0.8 cm	20.6*	2.9	2.2	5.0	10.9	7.2	3.8	11.4	1.0*
	+ 1.6 cm	9.2	20.6*	2.5	5.9	10.8	19.7*	2.3	15.7*	
	Levelled	16.4*		8.1		11.4		9.8		
2	+ 0.8 cm	3.3	5.6	16.5*	17.3*	7.6	23.9*	23.4*	17.1*	0.0
	+ 1.6 cm	9.0	10.8	9.1	13.2*	13.7	24.2*	17.3*	14.2*	
	Levelled	15.3*		5.6		3.7		13.1*		
3	+ 0.8 cm	6.5	9.7	15.5*	7.3	4.5	6.5	22.5*	12.2	0.5
	+ 1.6 cm	7.6	32.1*	15.5*	7.1	11.7	19.4*	22.4*	13.2*	
	Levelled	5.2		2.1		3.1		2.3		
4	+ 0.8 cm	9.6	15.5*	2.4	9.6	0.3	10.6	4.3	10.3	1.3*
	+ 1.6 cm	6.1	1.3	2.7	10.4	0.2	13.1	7.0	9.2	
	Levelled	11.4		2.1		9.4		2.4		
5	+ 0.8 cm	18.0*	11.9	1.1	1.9	7.6	27.7*	0.7	1.5	0.0
	+ 1.6 cm	11.9	1.3	1.1	4.5	5.1	24.6*	1.8	2.7	
	Levelled	7.7		1.2		7.3		2.2		
6	+ 0.8 cm	4.7	3.5	2.6	4.5	19.9*	6.4	1.1	0.4	1.1*
	+ 1.6 cm	21.5*	14.6*	10.2	6.1	22.8*	11.2	5.7	0.4	
	Levelled	4.2		3.2		3.0		2.9		
7	+ 0.8 cm	0.0	10.0	4.1	2.2	13.3	9.6	0.6	1.6	2.2*
	+ 1.6 cm	6.7	16.1*	5.6	0.3	12.2	9.8	1.9	2.0	
	Levelled	10.8		1.9		10.1		1.4		
8	+ 0.8 cm	4.5	20.8*	4.2	8.5	11.7	14.5	4.6	2.4	0.0
	+ 1.6 cm	2.4	3.5	4.0	11.1	16.0*	22.0*	6.9	8.0	
	Levelled	5.8		2.6		5.6		3.3		
9	+ 0.8 cm	5.9	19.3*	1.5	10.1	1.3	16.2*	3.1	2.9	2.3*
	+ 1.6 cm	23.3*	1.3	0.7	8.9	10.9	11.6	3.2	5.4	
	Levelled	10.0		3.8		9.1		1.3		
10	+ 0.8 cm	2.6	6.7	0.4	8.5	9.7	24.9*	1.9	0.7	0.0
	+ 1.6 cm	1.3	16.7*	1.8	1.9	17.1*	30.1*	2.8	7.9	

Lastly, a statistical analysis test was executed utilising the one-way ANOVA test to compare the mean difference between CMJ criteria across the five CMJ sets. The criterion of significance was set to be $p \leq 0.05$. Interestingly, the BA threshold percentage of the eccentric average force criterion manifests a significant mean difference across CMJ sets when compared with the other CMJ criteria ($F_{(4, 45)}$ = 5.768, p = 0.001). This finding indicates that there was a significance influence on the athletes' eccentric average force when the heights of the force platforms were being manipulated.

6.4 Discussion

Previous studies of BA in lower limbs (Goslin and Charteris, 1979; Holmes and Alderink, 1984; Berg et al., 1985) quantified asymmetrical differences based on left-right, or dominant-non dominant limb classifications (Section 2.7). Such variance in classifying asymmetry has raised misperception when comparing a study to another as they lack of uniformity. Another fundamental problematic issue was also the different methodological approaches executed. For instance, some researchers have used t-test for their analysis when comparing both limbs which reveals a tendency for the average difference to be zero, depending on the characteristics of the population being examined (Hvid et al., 1981; Beckett et al., 1992; Astrom and Arvidson, 1995; Sobel et al., 1999; Newton et al., 2006). Thus, this study has proposed a statistical analysis approach based on the agreement percentage between variables, aiming to interpret data into a more clinically sound relevance.

The first experiment of this study has utilised the mean absolute difference between limbs in order to provide a more realistic estimation of 'typical' asymmetrical differences between variables as executed similarly in study one (Chapter 4). Therefore, setting asymmetry thresholds based on mean ± SD of absolute difference between limbs provides a clinically accurate assessment tool to diagnose BA in a more robust manner. Consequently, the performance outcome has permitted examining a novel association methodology that relates the influence of a variable to one another in a more clinically sound prospect. For example, Newton et al., (2006) did not find any correlation between the CMJ Max Force and 1LCMJ Max Force as well as the isokinetic testing of knees' extensor and flexor muscles at 60°/s (This study has supported the same finding except for the absolute correlation of hamstrings muscle strength, r = 0.189*). However, the association of asymmetry agreement revealed that there are medium-high associations between CMJ Max Force and the aforementioned variables (77.1-80.7%). These high association percentages suggest that for every two variables carried out for comparison, there are three out of four (or even four out of five) athletes carrying the same diagnosis (i.e. balanced = balanced or asymmetrical = asymmetrical).

The asymmetry agreement levels of CMJ variables were mostly over 75% (3 out of 4 participants) when compared with the other variables found in flexibility, anthropometry, strength and 1LCMJ attributes. Interestingly, the hamstring flexibility was found to be one of the least variables that associated with any of the CMJ criteria.

The aforementioned high levels of asymmetry agreements between variables suggest that BA in CMJ's variables were developed likely as result of multi-factorial causes (i.e. the cause of the asymmetry performance in the maximum force production during CMJ could be as a result of asymmetry in one or more of the criteria of flexibility along with anthropometric or/and strength etc.) and, not due to the influence of a single variable only. Indeed, as after examining the summation of asymmetry agreement percentages, it was found that the percentages were between 70.1-83.3% for all the static, dynamic and single joint tests (Figure 2.1) when compared with the CMJ's variables. Lastly, such high levels of association in asymmetry agreements between lower limbs variables was greater than first anticipated in this study.

As for the second experiment on this study, Figure 6.1 has shown that percentages of BA in CMJ's variables went from 20% in the levelled platform CMJ set to 90% when the plates of 0.8 and 1.6 cm were added. These noticeable changes gave a clear picture of how LLD could dramatically influences the force platform profile (Figure 3.4) as it shifted the majority of the tested population from being symmetric to asymmetric.

In term of the CMJ sets when 0.8 cm were added to either leg, the existence of BA from the levelled force platforms CMJ set has differ in the standing body weight distribution and eccentric average forces only as half of the population developed an asymmetry as shown in Figure 6.2.

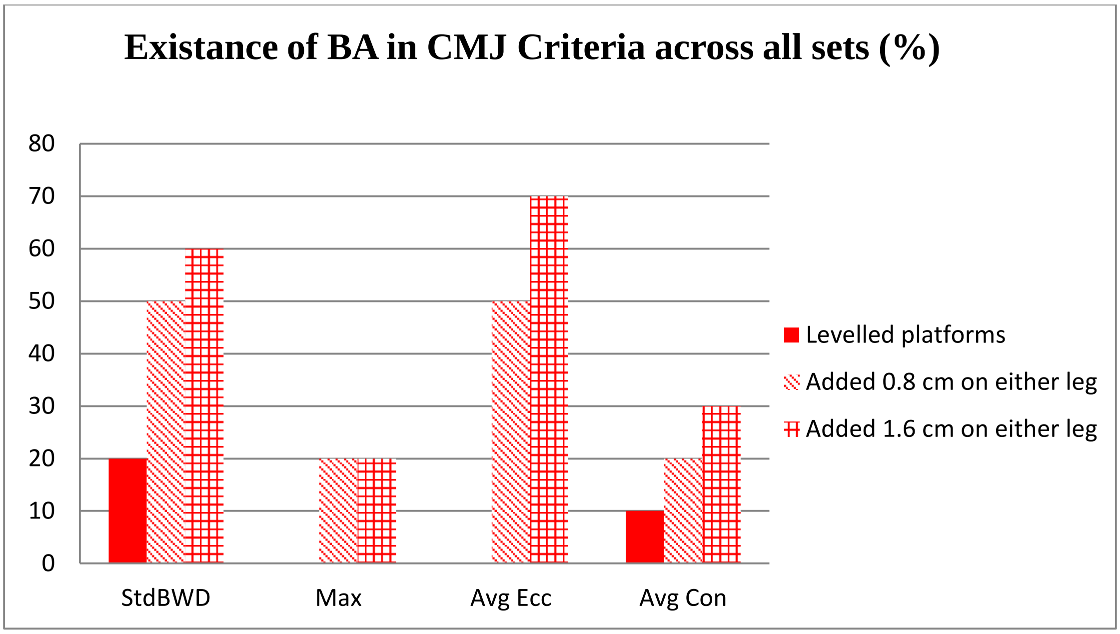

Figure 6.2: Percentage of existed BA in all criteria of CMJ after adding 0.8 and 1.6 cm plates on either leg (n=10).

Furthermore, when 1.6 cm was added to either force platforms, the parameters of CMJ have shown different observations than the levelled CMJ trials. Figure 6.2 showed that, the eccentric average force and standing body weight distribution (StdBWD) force exhibited a substantial increase in bilateral asymmetry as it jumped in the StdBWD from 20% to 60% and in the latter from 0% to be 70%. The maximum force criterion was the only one that did not changed dramatically when the height being manipulated across CMJ sets.

Interestingly, the two participants whom were diagnosed with BA in one of the CMJ criteria in the levelled CMJ set, have agreed to have BA in LLD and when the height was levelled for both of them the BA during the CMJ was nullified. Moreover, after discovering that the difference in average eccentric force criteria was statistically significant ($F_{(4, 45)} = 5.768$, $p = 0.001$) across CMJ sets, it was found that 50% of the population has benefited at some level from adding one or even two plates, as it helped them to decrease their level of BA in that specific criteria. Interestingly, two out of five participants (40% of the *benefited population*) had better results when the 1.6 cm was added to the force platform over the 0.8 cm plate (Figure 6.3)

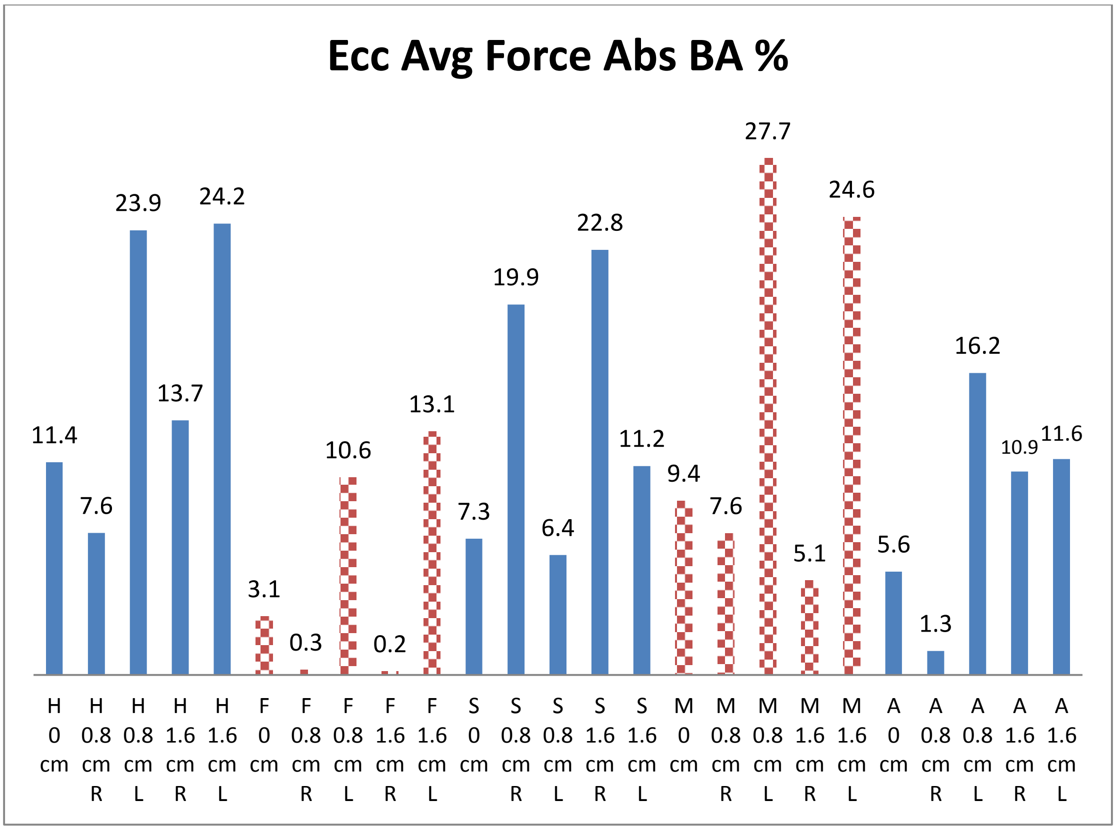

Figure 6.3: Chart of rectified BA percentages for Avg Ecc Force criterion across all CMJ sets (levelled, added 0.8 [plain blue bars] and added 1.6 cm plates [large checker red bars] on right and left legs) for the *benefited population* only (n=5).

Lastly, the effect of manipulating leg length when performing CMJ has showed a superior effect on the average force of eccentric phase during CMJ than the other criteria. This means in clinical relevance, that athletes with bilateral asymmetry in their leg length could enhance their performance during CMJ activities once they managed to correct their existed LLD.

6.5 Conclusion

Without definitive bilateral asymmetry thresholds for specific criteria in lower limbs, it would be difficult to classify athletes as whether or not they are functioning symmetrically. Such symmetry or asymmetry function, would require some degree of therapeutic intervention in order to optimise their function. Delightedly, this study has sat thresholds for 16 criteria across six different attributes (CMJ, flexibility, anthropometry, strength, NFPTs and 1LCMJ performances). Establishing associations between variables based on "asymmetry agreement test" was a novel statistical approach to examine the influence of a criterion against other. Such novel approach, has provided a more meaningful insight in a more clinically sounds comparison between key criteria in the lower limbs. The results from both parts of this study suggested that, when executing CMJ, in reality the majority of athletes would carry on at least one bilateral asymmetry in their lower extremities and that would influence one of their multi-joint or functional tasks. However, a single criterion that exceeded the threshold does not necessarily affect athletes' performance when competing in sport and, they would still be able to operate mostly injury free (assuming that subjects were participating in a non-contact sport). As a consequence, this study has shown that bilateral asymmetry does have a cause-effect relationship in order to optimise the performance of CMJ as the results from the comparisons have showed strong associations (at least 68.2%) for every comparison between any two given variables. Nevertheless, the severity and combinations of asymmetries should be examined alongside other factors relating to the loading characteristics and mechanisms of specific movement that might enhance performance or even could lead to injury risk.

Furthermore, the results from the second experiment of this study were consistence with the findings from the first one as the asymmetry agreement percentage between CMJ attribute and the flexibility, anthropometric and strength attributes was the highest in the anthropometric attribute as the thigh circumflex discrepancy was mainly the highest variable associated with any CMJ criteria (StdBWD, maximum force and average concentric force (second highest was the average eccentric force)). In addition to the high association in the anthropometric attribute, LLD has also supported the same finding as the association between LLD and the CMJ criteria varied between 75.7-81.3%. Furthermore, when the height of the force platforms was manipulated, participants have exhibited a better performance outcome (became less asymmetric). Therefore, such findings support the fact that anthropometric, along with other attributes; have influence over the force platform profile. In contrary, the flexibility of the hamstrings has showed the least influence when associated the criteria of CMJ. This finding, suggests examining the muscle’s activation levels during the concentric and eccentric phases of CMJ as a stronger activation level could suggest an unstable knee on either side. This effect could be as a result of the nature of the body mechanics during the eccentric phase during CMJ as this phase requires precision when lowering downs, the body to be prepared for the concentric phase. Thus, manipulating leg length in this phase discomforts the body's structure and alter it kinetics more considerably. Nevertheless, a weak antagonist muscle group could elevate muscle activation as a protective mechanism from being over stretched which could hinder the agonist muscle group from executing a maximal effort (i.e. level of hamstring muscle’s activation could affect the activation level of quadriceps muscle group during concentric phase of the CMJ). Another example is, taking extra precaution by performing a submaximal effort when kicking a placed ball to prevent extra stretching (10.9 %) to the hamstrings muscle group (Graham-Smith, and Lees, 2002). Such speculation to correct some of the BA in CMJ criteria could be a great suggestion for future work to be investigated thoroughly. Lastly, rectifying leg length by clinicians in the form of inserting insoles to the shorter leg of athletes with LLD during exercises or competition could be highly beneficial to them as the second experiment of this study has shown a great potential in optimising athletes’ performance as well as balancing the weight loading between limbs in order to reach the most possible symmetrical profile.

After examining the association between CMJ’s variables with key variables in lower limbs. It was recommended to run a further statistical analysis to investigate the association between CMJ with running gait criteria as they are both reflected as functional performance tests. The investigation was conducted to identify (using asymmetry agreement test) athletes whom have asymmetry in both functional performance tests.

7.0 STUDY FOUR

Title: Investigation into asymmetrical analysis on two functional tests: running gait and countermovement jump.

7.1 Introduction

Bilateral asymmetry is a term used to describe deviations in functional performance between left and right limbs. The underlying premise of bilateral asymmetry (Figure 1.1) suggests that substantial deviations in kinetics during running tasks or CMJ would create compensatory movements, modifying kinematic patterns and eventually impacting performance (running or/and CMJ). Such influence, if being constructed, could enhance athlete's performance and, if BA was over used or neglected over a period of time during an intense competitive season, could lead to a risk of injury. Furthermore, enhancement of performance of some tasks (i.e., crossing legs often toward one side due to limb dominancy) could occur due to repeating the same movement unilaterally over time. Whilst the theory seems plausible, limited evidences exist to validate the argument of BA development in athletes (Section 2.4). Before associating BA with injury, clear criteria and thresholds need to be established for different tests and tasks of interest in order to reach such aim. Thus, the purposes of this study were to set thresholds and to examine the level of 'asymmetry agreement' between diagnoses of asymmetry for unilateral (running) and bilateral (CMJ) functional movements.

Lastly, the purpose of gait analysis was to analyse the kinematics of running. Whilst it is acknowledged that gait characteristics vary between individuals, this study was interested in quantifying movement (kinematics), in order to identify left versus right limb asymmetry.

7.2 Methodology

One hundred and forty-four athletes from a sport academy centre participated in this study. Luckily, the proposed protocol was accepted by the academy and, to be as part of their preseason screening protocol. The age of the young athletes has ranged between 12 and 18 years old. The bilateral asymmetry analysis bundle was executed at an indoor set-up to examine the association between the criteria of running gait and countermovement jumps using the asymmetry agreement test. The running gait protocol required installing four high-speed cameras (Quintic high-speed live USB2, Quintic Consultancy Ltd, UK) that been connected to a main computer in order to record athletes simultaneously at 125 frame/s while running at fixed speed of 12 km/h for 30 second on a treadmill (ELG Treadmill, Woodway INC., USA). Cameras were sat-up in four positions around the testing area (Anterior, posterior and both lateral sides). The Quintic Biomechanics software was used to extract the heel strike and toe-off parameters from the recorded videos during the stance phase (Figure 7.1). The means of contact time, swing time and stride length over 6 strides were calculated. BA was expressed as a percentage (AAV %) and was calculated by dividing the difference of both legs over the maximum score of either right or left leg score (Equation 1). The asymmetry threshold percentage (Equation 2) of each parameter was determined as the mean absolute difference plus standard deviation of all athletes (section 3.3.1).

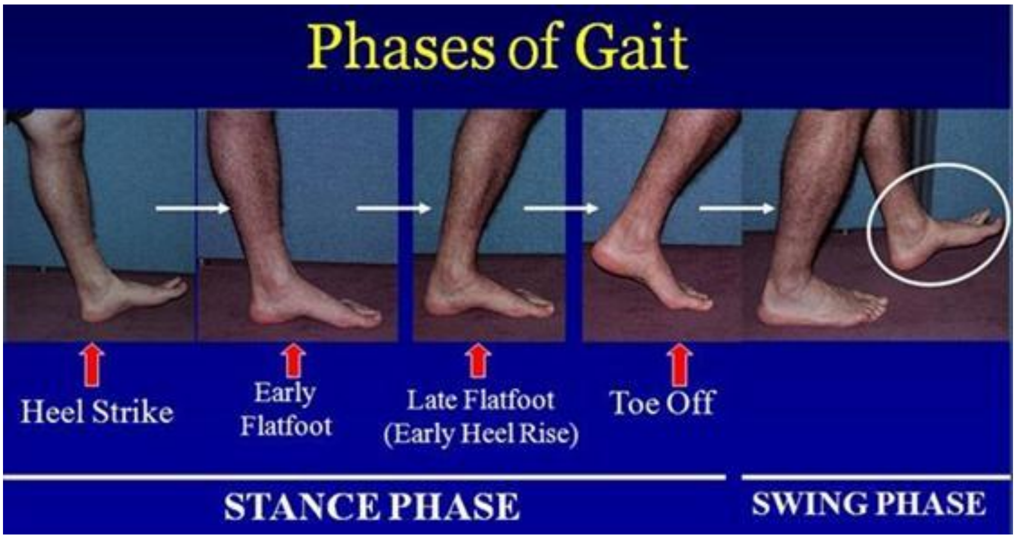

Figure 7.1: Phases of Gait (foot education, 2015)

The protocol of running gait started with setting-up the equipment. Four high speed video cameras were installed around the treadmill in an indoor laboratory (Figure 7.2). Regarding the video cameras, it was important that the cameras are perpendicular to the treadmill's belt to attain footages from the frontal, rear and sagittal planes of the entire movement and, one of the side cameras was positioned closer to the level of the belt to attain accurate assessment of foot contact during the stance phase.

Athletes had to sign the consent form (Appendix B2) prior to testing and were asked to wear comfortable shorts, a vest (or no shirt at all) and running shoes. It was important that joints were clearly visible for the ease of identification and accuracy during the subsequent analysis. The test procedure involved standing close to the athletes and the safety stop button is within hand reach to ensure athlete's safety during running. Athletes were instructed to stand in the middle of the treadmill surface and hold onto the rails and then, instructed to walk as the treadmill speed increased and to gently break into a jog when walking can no longer be sustained. After that, the treadmill was set at 12 km/h which is found to be an appropriate speed to maintain a confident running stride during the video recording and, was maintained for approximately 30 seconds before being brought to rest. Following this short period of familiarisation, the process was repeated for actual testing.

To ensure the trials validity a number of components were required to be checked. Firstly, athletes had to appear relaxed and gave verbal feedback as to whether they were feeling comfortable at the treadmill pace. Secondly, the rear camera was set-up at belt level to attain an accurate assessment of the instant of foot contact and toe-off for the measurement of contact time. Thirdly, earlier before commencing the testing, the treadmill belt speed was pre-set exactly on 12 km/h. Choosing the aforementioned speed was based on the results of a pilot study on eight subjects which will be presented afterward in the results section (Section 7.3). Then, the belt speed was checked from the same high speed video analysis. This procedure was important for the accurate determination of stride length and step frequency. Lastly, a minimum of five contacts per foot were analysed as taping numerous consecutive heel strikes was optimal in assessing BA in running for some criteria of great within-limb variability as described by Zifchock & Davis (2008) and, the average and standard deviation was determined.

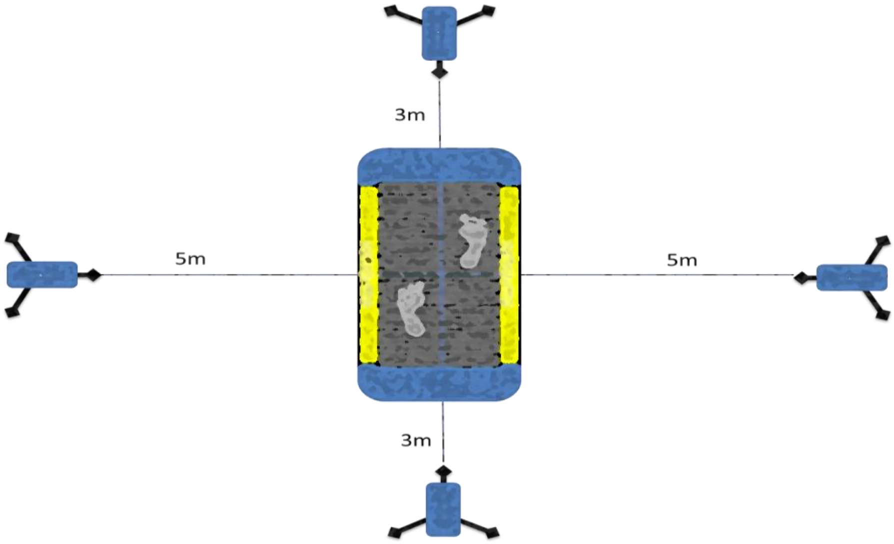

Figure 7.2: Cameras setup location for the treadmill test

A speed of 12 km/h was set during the testing and the extracted parameters were used in order to examine the association between the criteria of running gait and CMJ using the asymmetry agreement test. This chosen speed was based on results generated from a clinical investigation of eight academy athletes that underwent a battery of testing involving on running on a treadmill for 30 seconds on different speeds (8, 10, 12, 14 and 16 km/h). During the 30 seconds trail, six strides were taken for analysis to compare how the bilateral asymmetry of running gait's parameters may differ as the speed increases across trials. Lastly, the reliability of running gait parameters were presented in Table 7.1.

Table 7.1: Reliability results of running gait parameters for mean difference, typical error, SEM, ICC, Pearson's r correlation and CV (%) (n=10).

Variable	Mean Difference	Typical Error	SEM	ICC	Correlation r =	CV (%)
Contact Time	0.04	0.06	0.12 s	0.99	0.965	9.4
Swing Time	-0.01	0.03	0.27 s	0.99	0.997	29.7
Contact Length	0.04	0.26	0.58 s	0.98	0.977	19.9

As for the CMJ test, Three CMJs were performed on two adjacent force platforms (Kistler 9286AA, Kistler Group, Switzerland) sampling at 1000Hz (section 3.3.4). Left and right leg forces were summed to establish total force and the point of maximal displacement used to define the transition between eccentric and concentric phases. Average forces in the eccentric and concentric phases as well as, the peak forces were extracted. Bilateral asymmetry was expressed as the mean of absolute difference between limbs percentage contributed to the total force.

7.3 Results

Figure 7.3 shows different results of bilateral asymmetry percentages of running gait parameters for the eight athletes when being tested across different speeds. Contact and swing times threshold during 12 km/h falls in the middle when compared with other speeds. Whereas, the BA% of stride length has showed a different pattern.

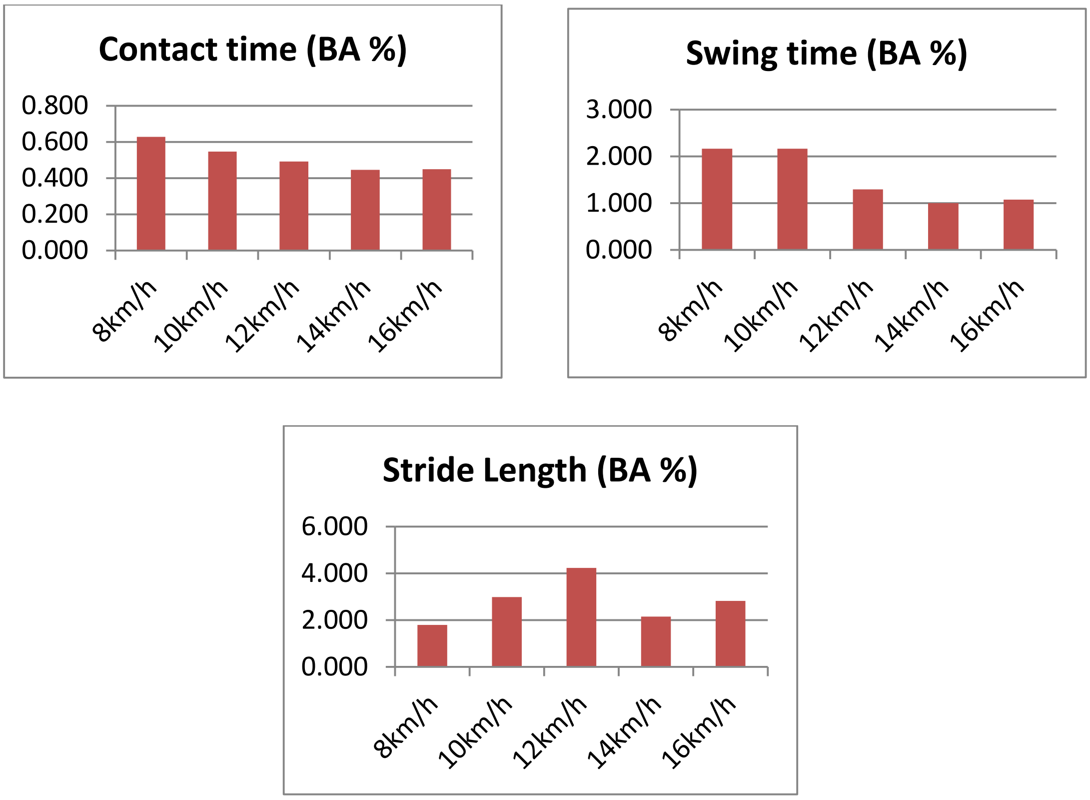

Figure 7.3: BA% of running gait parameters across different speed (n=8)

Moreover, athletes have showed a predicted ascending in their stride length as the speed increases across the trials. Furthermore, the average swing time has shown an increase as the athletes have increased their speed during the testing. On the other hand, contact time has showed a predicted result as the time was descending consistently whenever the speed was increasing (Figure 7.4).

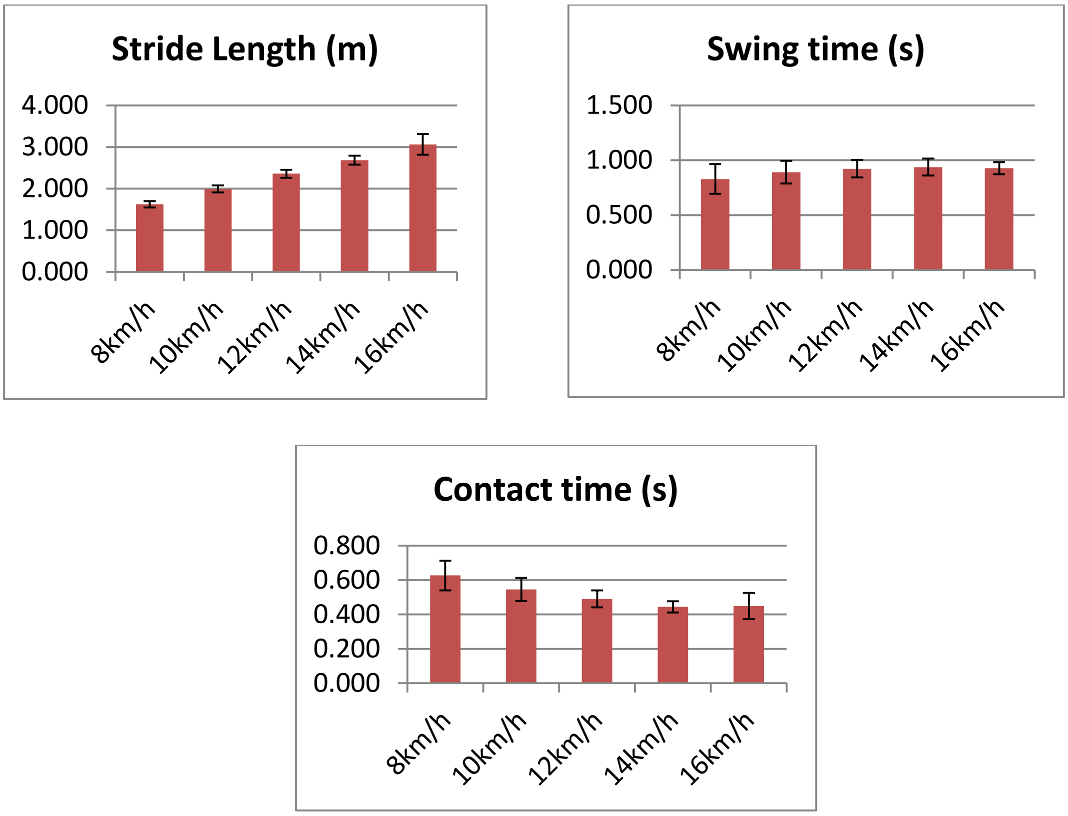

Figure 7.4: Performance of running gait parameters across different speed (n=8)

In order to classify an athlete having an agreed asymmetrical difference in any parameters of running gait (contact time, swing time and stride length) or the parameters of countermovement jump (peak force, averages of eccentric and concentric forces), at least one of the three criteria in both functional tasks had to exceed it/their thresholds (Table 7.2). Interestingly, athletes exhibited highest asymmetry performance in the parameter of average eccentric force as thirty-seven of the tested population (Total n=144) have exceeded the threshold. On the other hand, peak force was the least frequent parameter exhibiting asymmetry among all the tested athletes (n= 11).

Table 7.2: Asymmetry threshold % and (asymmetry frequency) for each parameter (n= 144).

CMJ	**Peak Force**	**Avg Ecc Force**	**Avg Con Force**
Threshold %	7.6% (11)	11.7% (37)	7.3% (12)
Running	Contact Time	Swing Time	Stride Length
Threshold %	9.1% (16)	5.3% (19)	8.9% (16)

The presented threshold percentages in Table 7.2, have diagnosed a number of athletes for being bilaterally asymmetric in their performance once their performance in each test has exceeded the generated cut-off in that specific criteria. Thereby, sixty-four athletes have exhibited an asymmetry in at least one of the two functional tasks (CMJ only 30, running gait only 22 and in both tasks 12 participants). The results in table 7.3 have shown that an agreement of 18.8% between the functional tests based on the diagnosis of asymmetry agreement test.

Table 7.3: Existed asymmetry percentages in both functional tasks along with, the association between them. The association was presented as a percentage and performed using the asymmetry agreement test.

	CMJ only	**Running only**	CMJ & Running
No. of Asymmetries (%)	30 (20.8%)	22 (15.3%)	12 /144 (8.3%)
Total Asymmetries (%)	-	-	64 /144 (44.4%)
Agreement with NO asymmetry (%)	-	-	80 / 144 (55.6%)
Agreement with asymmetry (%)	-	-	12 / 64 (18.8%)

7.4 Discussion

Establishing thresholds for key criteria in running gait and countermovement jumps tasks would assist clinicians to diagnose any existence of bilateral asymmetry in athletes' performance. Such cut-off percentages, can be utilised as an accurate and objective assessment tool to measure the difference in performance between lower limbs in specific functional tasks. Thereby, tackling BA in performance in its early stages would enable rehabilitation team and couches to alter their plan of cares in order to enhance the performance of the athletes.

When comparing the results (Table 7.2) of the threshold percentages in the running gait with a recent study (Pappas et al., 2015), it was found that the threshold percentages were not similar to one another for each criterion. Such variance in results, could be as a consequence of a different asymmetry index that been used in each study. The asymmetry index in Pappas's study was (ASI = $2|L - R| / [L + R]$) and, has been used also by Karamanidis et al., (2003) previously. Pappas's absolute symmetry index was a modified version of the symmetry index proposed by Robinson et al., (1987) as the original formula called symmetry index (SI) and, the formula was SI = 2(*non-injured side – injured side*) / (*non-injured side* + *injured side*) x 100. However, Pappas claimed that: "It protects the data from directional bias, thus providing an estimate of "laterality free" (absolute) asymmetry as percentage of total (both-sides) value". However, Pappas has contradicted his decision and admitted that his elected index has a tendency to calculate in general, a higher value of asymmetry percentage. Moreover, the same different outcome was observed when the absolute asymmetry value was compared with the asymmetry index of Zifchock, R. A. and Davis, I. (2008) as they have formulated their index based on a designated preference of the tested leg (asymmetry index = x1 - x2 / preferred leg x 100). Lastly, the only clinical reasoning claimed by Pappas's for not choosing the same asymmetry index used in this proposed study (AAV%) was that, the absolute asymmetry value percentage (AAV%) = |*L leg – R leg*|/(maximum of either leg) x 100 produces a conservative estimate of bilateral asymmetry. It is believed that such suggestion proposed by Pappas was made, due to the small sample size used in his study which requires adding some controlling factors to his asymmetry index equation in order to produce a sensible outcomes results. However, this current study does not confine to the same constriction. Thus, choosing the formula of this study appears to be rightful. Unfortunately, no comparisons were able to be made between the results of Pappas's study and this current study to indicate which methodology is superior over the other in term of using the most clinically sound threshold percentages as the population (adults versus Adolescences) and the cadence's speed (16 versus 12 km/h) were different in both studies.

The decision of pre-setting the speed at 12 km/h in order to generate the thresholds for the parameters of running gait was pertaining to the most suitable scores and falls in the middle of the spectrum of the generated outcomes from the aforementioned speeds as it can be seen in the results of Table 7.4. The proposed speed for this study, which believed to mimic the athletes' daily activities when competing in sport were 8, 10, 12, 14 and 16 km/h. It was found that 12 and 14 km/h were the most clinically relevant speeds to generated the thresholds based on them. However, due to the nature of population of this study (Adolescent), it was found that the speed of 14 km/h was not too easy for the older athletes to execute and, on the other hand, was challenging for the younger ones. Thus, based on the clinical judgement of the author and, considering the safety of participants, it was decided to set the speed of the main study in this chapter at 12 km/h.

Moreover, one of the interesting findings in table 7.2 was that, the eccentric average force during the countermovement jump was once again, the most asymmetric criteria in the CMJ attribute and, that has unveiled a poor movements control when descending during a CMJ in adolescence also. Therefore, the consistent variance in the average eccentric force urges the needs of examining all the attributes that might affect this specific criterion. Nevertheless, revising thoroughly the force platform profile within repeated training sessions could rectify any existed bilateral asymmetry by its own (biofeedback) without planning for any sophisticated interventions.

The proposed approach that generated precise threshold percentages when examining the running gait and countermovement criteria has showed a superior advantage over the questionable trends that examine bilateral asymmetry in current practise. Indeed, as adopting arbitrary threshold percentages ranging between ten to twenty percent would misdiagnose athletes as described earlier in Section 2.7 (10%, Burkett, 1970; Dauty et al., 2003 and; Schiltz et al., 2009. 15%, Baumhauer et al., 1995; Bennell et al., 1998 and; Croisier et al., 2002. 20%, Fowler and Reilly, 1993; Croisier et al., 2002 and; Myer et al., 2004). Furthermore, in term of the statistical analysis approach, past studies have adopted correlation and repeated measures of analysis of variance to compare tests of asymmetry (Daly and Cavanagh, 1976; Hvid et al., 1981; Beckett et al., 1992; Astrom and Arvidson, 1995; Livingston and Mandigo, 1997; Sobel et al., 1999; Rahnama et al., 2005; Newton et al., 2006), this study has examined the association of asymmetry agreement test for the criteria of two functional tasks.

This novel statistical approach has unveiled that, among the one-hundred and forty-four athletes, it was found that sixty-four one have exhibited BA in at least one of the six tested criteria. Moreover, it was found that twelve athletes out of the sixty-four ones (18.8%) had an asymmetry in at least one of the criteria of each functional task. This key finding suggests that, countermovement as well as running gait were a distinct and separated functional movements. Interestingly, the tested population have showed that, athletes have displayed more BA while performing CMJ (20.8%) than when they were running (15.3%). Thus, it is essential to assess asymmetry difference found within each functional behavioural task separately. Lastly, This proposed method, would provide a more holistic approach in understanding the effect of bilateral asymmetry in athletes and to allocate where precisely and effectively focusing the training programme in order to enhance their performance.

7.5 Conclusion

Examining the bilateral asymmetry agreements between the agreed asymmetrical attributes (running gait and CMJ) concludes that, the functional behaviour bilateral asymmetry in lower limbs manifest themselves in athletes' population by around twenty percent. Therefore, examining both unilateral and bilateral functional tasks has showed superior clinical relevance over screening one of them when examining one of the tasks to diagnose asymmetry in lower limbs in order to assess the athletes' level of asymmetry as a tool to predict their performance.

This study has several advantages; firstly, it has compared two distinct functional behavioural tasks (Figure 2.1) as there was no study that performed such comparison between functional tasks previously. Secondly, it has revealed statistically (using the asymmetry agreement test) that, among the examined population, there was an approximately twenty percent who agreed to have a bilateral asymmetry in at least one of their tested criteria in both functional tasks. Therefore, its recommended that to consider including more than a single functional task when investigating bilateral asymmetries in lower limbs in athletes when executing their periodic comprehensive assessments as asymmetry in one functional task my not fully trigger the rehabilitation team's attention to identify exited asymmetry that hinders athletes' performance. Such complex examination into the relationships between functional tasks, could offer superior clinical understanding of the associations between the body's kinematics. Thirdly, the speed of 12 km/h was found to be clinically relevant to examine BA in running gait for adolescents however, higher speed seems to be more appropriate when performing similar test on older athletes. Fourthly, this methodology can provide a useful insight to practitioners into how to conduct low-cost studies in professional set-ups as this study was conducted utilising a treadmill, a pair of force plate platforms and few slow-motion cameras only rather than using time-consuming equipment such as three-dimensional gait analysis in order to extract similar parameters or by operating expensive systems like isokinetic dynamometers. Lastly, this study could be implemented as a benchmark for other similar studies as it has provided norms based on large sample size of healthy athletes whereas several studies (Zifchock et al., 2006; Zifchock and Davis, 2008 and; Pappas et al., 2015) have displayed a small recruited population (n= 49, 52 and 22 respectively). In addition, it can lessen the time consumed by future studies as no need to recruit healthy subjects when conducting a study on subjects without any medical conditions for the sake of generating bilateral asymmetry norms for comparison purposes.

8.0 DISCUSSION

This thesis has offered a novel insight in a number of key topics that is related to bilateral asymmetry examinations in lower limbs. Seven studies were conducted in order to answer a number of hypotheses in BA that were under speculation. Each of which, had it is own aims and answered a specific part of the thesis's questions. The first study was conducted to examine the reliability of the executed tested (Table 4.3) for all the upcoming studies and, the results were compared with related studies found in the literature with similar criteria. The reliability results showed comparable findings with similar previous studies as discussed in Section 4.2 which was a key outcome to proceed for the upcoming studies. Following that, were the fundamental two studies in this thesis (Chapters 4 and 5), as they have established threshold percentages of a number of key criteria within specific attributes (Anthropometrics, flexibility, NFPT, CMJ, 1LCMJ and Strength) for elite and sub-elite athletes.

The decision of choosing CMJ criteria based on body weight only was derived from an auxiliary study were sixty-three athletes underwent a battery of testing to compare their asymmetry across additional loads during the trails. Interestingly, athletes exhibited similar bilateral asymmetry percentages in their CMJ criteria across trails (except for the average concentric force at the trail of CMJ with forty percent extra body weight). Such result suggested that, the criteria of CMJ based on body weight only were appropriate to be utilised when associating it performance with other key criteria of lower limbs. After that, an investigation was conducted to examine the level of asymmetry agreement between countermovement jump criteria with other key criteria from different attributes. The criteria of CMJ were the yardstick in this analysis aiming to explore the associations between criteria and how they influence one another as a structure (Chapter 6). Interestingly, the association between criteria was found to be 75% (3 out of 4 subjects had the same agreement) between variables or even higher. A further experiment was conducted in Chapter 6 to investigate the influence of manipulating the leg length on CMJ criteria. Interestingly, it was found that LLD has obvious effect on decreasing as well as increasing CMJ criteria (significantly on Avg Ecc force). The last study was executed to explore the possibility of the cause and effect relationship (Figure 1.4) between running gait and CMJ criteria thereby, an investigation based on the association of asymmetry agreement between both attribute was done (Chapter 7).

As a consequence, there were reasonably consistent bilateral asymmetry found in healthy athletes throughout all the studies in this thesis. The asymmetries in performance were diagnosed in functional activities like CMJ and running gait, multiple or single-joint tasks such as 1LTH and isokinetic testing. Bilateral asymmetries were also found in static examination tests such as the measurement of thigh circumflex. The threshold percentages produced in this thesis for key criteria in lower limbs would serve as critical cut-off values for sports rehabilitation clinicians as well as strength and conditioning coaches for the elite and sub-elite athletes. If the percentage of BA was found to be more than the suggested threshold percentages, it would raise concerns regarding potential increased risk of injury over a period of time due to overuse which could provoke BA and subsequently straining the musculoskeletal structure. Whereas, as shown in the second experiment of study 3 (Section 6.3), that manipulating the leg length to level the discrepancy between left and right legs has rectified the BA in some athletes positively and allowed them to perform their CMJ more symmetrically. Such positive results could highly suggest the rectifying BA could enhance athletes' performance as they will be performing more symmetrically specially when competing in sports that require more bilateral movements such as rowing.

This thesis has overwhelmed the deficiencies found in previous researches, as it has clinically diagnosed a number of key criteria for bilateral asymmetry based on a novel approach using the mean of absolute asymmetry values. This measurement has demonstrated more meaningful and precise percentages for clinical cut-off points to diagnose bilateral asymmetry in performance. The threshold values' interval ranged from as high as 38.1 down to 0.8 %. Therefore, being diagnosed above any proposed threshold is considered to be abnormal and, interestingly most of the threshold percentages were not similar to the 15% commonly used to define BA in lower limbs.

The results of this research have supported the findings of previous researchers (Daniel et al., 1982; Mangine, 1990), as it showed that isokinetic strength (OKC) testing alone is not a sufficient indicator to ascertain dynamic functional capacities. On the other hand, performing CMJ (CKC) testing on double force-platforms appears to be more holistic in identifying bilateral asymmetries in lower-limbs. This finding does not rule out the fact that, isokinetic measurements were still imperative procedure for the assessment of strength characteristics as both tests were commonly used for healthy subjects as well as the ones under rehabilitation programmes in order to monitor their progress. The same exact fact has applied as well to the neuro functional performance tests, as one attribute may not also be insufficient to measure the level of athletes' performance in dynamic tasks. Therefore, associating several tests is highly recommended to achieve an accurate assessment for subjects with bilateral asymmetries, as it provides a clear picture of the functional level of athletes as well as their readiness to return to competition. This suggestion was also consistent with the findings of previous studies (Harter et al., 1988; Gray et al., 1992; Theoharopoulos et al., 2000; Jones & Bampouras, 2010), which stated that no one single adequate measure of function is enough to predict BA.

Moreover, establishing thresholds for sub-elite athletes has raised a question about the effect of certain kinematic and kinetics characteristics in certain sports that may influence the musculoskeletal structure in term of their performance bilaterally. Thereby, this thesis has provided an insightful answer to such question by comparing four sport-specific groups of elite-athletes. Interestingly, differences in the threshold percentages were found across all sport groups for all tested criteria. However, when analysing these findings statistically across all group using one-way ANOVA test, the result has revealed no significant difference between the groups except for the soccer players when the isokinetic testing of the hamstrings muscles has been examined across the sport groups. Such finding was significant by itself as it has answered an intrinsic research question in this thesis (Section 1.1). However, when the threshold boundary test was conducted on the same population, different outcomes have revealed. As cricketers' thresholds were the most frequent ones to fall outside the threshold boundary as seen in Table 5.5 (Cricket = 6; Soccer and Track and field = 5; Rugby = 2). Such results have suggested that, rugby as a sport, does not have a great influence on athletes to perform asymmetrical manoeuvres which may enhances building up an asymmetrical profile on them. Furthermore, the generated sport-specific norms could be used as a great benchmark chart between sport clubs since the fundamental aim for practitioners of elite sport clubs is to acquire a clinically relevant diagnostic assessment tool that could provide a holistic insight current physical status of the athletes and, that may pave the way to tackle areas with potential risk of injury. Nevertheless, it has also filled a great gap in the literature where there was a demand of reaching supreme performance levels when competing in sport as this research has provides understandings about the potential influence in how manipulating criteria in lower limbs could be beneficial in rectifying bilateral asymmetries in lower limbs. This research has also, provided a solid platform in terms of setting norms using the same methodological approach that can be tailored to meet other sport-specific groups or certain demands.

One could argue the sufficient number of criteria that can provide a significant understanding when investigating bilateral asymmetry in lower limbs in order to predict potential injury risk or enhancing performance. For that, several researchers and practitioners (Mangine et al., 1990; Theoharopoulos et al., 2000; Newton et al., 2006; Impellizzeri et al., 2007; Croisier et al., 2008) have combined two or more criteria to answer such speculation or have recommended in their studies a further complex examination between attributes. Delightedly, this thesis has considered integrating some of previous recommendations in the literature when formulating it aims as well as, answering a number of arguments in the dilemma of bilateral asymmetry (Sections 6.4-5). Furthermore, study three has investigated the agreements between the criteria of CMJ and a number of key criteria found in different attributes (1LCMJ, anthropometric, flexibility, strength and neuro functional performance tests). All criteria were carried out for analysis using the association of asymmetry agreement as well as the Pearson's correlation tests. The results have shown that the association of asymmetry agreement between the criteria of CMJ and all tested criteria were mostly above 75% (three out of four subjects in each criterion had the same diagnosis in performance "balanced-balanced" or "asymmetric-asymmetric"). This novel test that examines the association between key criteria in in lower limbs has unveiled meaningful relationships between criteria that Pearson's correlation test was not able to picked out.

This thesis has also examined the asymmetry agreement between two functional behavioural tasks (Running gait and CMJ), which has not been examined previously. Remarkably, the association of asymmetry agreement was only around twenty percent. Therefore, the findings of this thesis suggest that, no single attribute by it is own, is enough to predict bilateral asymmetry in performance within sports specific tasks and, that agreed with what has been speculated previously in the literature (Mangine et al., 1990; Theoharopoulos et al., 2000; Newton et al., 2006; Impellizzeri et al., 2007; Croisier et al., 2008). Having said that, without definitive threshold percentages for key criteria in lower limbs, it was difficult to classify an athlete from being symmetric or not. Thus, assessments based on the proposed bilateral asymmetry analysis bundle could offer a made-to-order rehabilitation interventional plan based upon the results produced from examining each individual.

This study has fruitfully established associations between key criteria in lower limbs based on the diagnosis of "asymmetry agreement test" which was a novel statistical analysis approach that has examined associations between variables. Interestingly, the aforementioned test has shown similar agreements between the results of both investigations done in this thesis (Section 6.3) as the first part has discovered that the criteria of anthropometrics were the most agreed ones when the percentages of asymmetry agreement were calculated between CMJ and the other attributes (strength, flexibility and 1LCMJ). This finding suggested that around 75% or even higher in any given sport club/population would have a bilateral asymmetry in one of the countermovement jump's criteria as well as other key criteria in lower limbs. Such high association percentages manifested themselves strongly once again during the generated results of the second experiment in chapter six as correcting the discrepancy of leg length for the participants whom exceeded the threshold percentages during their CMJ have benefited from the intervention and managed to jump more symmetrically. The association was found especially during the eccentric phase as it has shown great and immediate symmetric effect on their force platform profile. Such result, has stressed again how beneficial was this methodology to correct some of the bilateral asymmetry criteria during CMJ which can be reflected in clinical applications as adding an insole into the shoe of the shorter leg has balanced the weight distribution between both legs with athletes whom diagnosed with leg length discrepancy allowing them to jump as symmetric as possible and that could highly optimise their functional performance.

Undesirably, this research did not include or utilise some factors when the criteria were chosen to diagnose BA in lower limbs. For example, a number of criteria in the kinematics of movement, as they could be considered a bit subjective between clinicians when choosing the measured items (i.e. which part of foot touches the floor first during initial contact when running on treadmill as not all participants touch the floor with their heels) as some measurements may provide further understanding of unexpected movement that could affect other criteria when performing a functional task (For example, excessive shifting of the trunk due to scoliosis could affect one of the step's parameters during running gait). Additionally, the indefinite criteria which might affect the CMJ such as power and take-off velocity as reported in the literature (González-Badillo et al., 2010). Although, integrating electromyography (EMG) may offer further insights into load distribution during the countermovement jumps however, it was not feasible to be included in the bilateral asymmetry analysis bundle (BAAB) as the installation of the device on athletes consumes a considerable amount of time even which could affect the sample size of each study dramatically.

Hopefully, with more new technologies developing recently between time to time in the field of biomechanics, it would be much reliable, affordable and easier to conduct multiple examinations during specific single or multi-joint task using one interface that control several variables concurrently which could lessen the effort and time considerably when handling large numbers of data. For example, the use of MVN BIOMECH system, which is a full-body suit that uses inertial sensors to detects the kinematics of movement (Xsens Technologies, US), has been shown to be a very easy and useful system to be used by few practitioners (i.e. Raggi et al., 2008) as it offers easy installation on participants which can be utilised as a real-time biofeedback device during gait training or movement in general.

Lastly, the underlying premise of bilateral asymmetry (Figure 1.1) in this research has two controlled factors (fatigue and previous injury) as they could directly affect the generated data of each criterion thus, fresh and non-injured athletes were only carried out for analysis and that needs to be considered in any future research. Moreover, the aforementioned premise has also acknowledged the measurements of the kinematics of movement such as muscle initiation timing and muscle’s recruitment.

This research has selected criteria that can be measured objectively only during functional behavioural tasks (i.e. countermovement jump or running gait). For example, the forces during CMJ (maximum force and the average of eccentric and concentric forces) were carried out for analysis only and it would be recommended to include criteria from such factors to add another dimension to the assessment protocol by integrating a qualitative measures to it (i.e. position of body parts) or more detailed quantitative measures during movements (joint's angle). Therefore, it is recommended for future studies that when examining CMJ to include the aforementioned criteria as using the force platform and the electromyography concomitantly may provide a further understanding of the force production during the whole countermovement jump trial (concentric and eccentric phases).

9.0 CLINICAL APPLICATIONS AND RECOMMENDATIONS

This research has offered a number of recommendations which can be clinically beneficial at the field of sport rehabilitation. Firstly, and for most, it has generated thresholds of bilateral asymmetry for key criteria in lower limbs. Once these thresholds been exceeded in athletes, a further thorough assessment would be advised as athletes with multiple incidences of bilateral asymmetry in several criteria could strongly suggest that they could have a decreased level of performance when competing at sport.

Other clinical application that has been derived from these thresholds was, offering a diagnostic tool to monitor athlete's performance. The criteria have been categorised based on different levels of function, which starts from basic static test (i.e. the measurement of calf circumflex) until reaching criteria from functional behavioural tasks such as the maximum force of CMJ. For example, if an athlete has exceeded the threshold of one of the criteria within a task (multi-joints or functional), this could be as a consequence of one or more of the criteria in static, dynamic or even single-joint tests being exceeding the BA threshold and causing such asymmetry in performance and vice versa.

This research has another fruitful advantage as it provided off-the-shelf norms for BA in lower limbs for sport-specific groups of elite-athletes. These norms can be highly beneficial for practitioners in professional sport-specific clubs to benchmark with (since sharing such knowledge among most the top-end professional sport clubs is usually not favourable).

Furthermore, this research has also offered a novel statistical approach to examine the relationships between criteria using the association of asymmetry agreement test. Such statistical approach has provided a clinically sound relevance for the influences derived from one criterion to another as the results have shown that the associations of asymmetry agreement tests were mostly 75% and even higher between every two variables. Such findings identified that bilateral asymmetry criteria in lower limbs manifest themselves in athletes' population distinctively. Thus, no single attribute (strength’s criteria alone) could diagnose bilateral asymmetry during functional tasks. Nevertheless, the last study in this thesis has also supports the aforementioned finding as it has suggested that, around twenty percent of the tested population have agreed to have asymmetry in their both functional behavioural tasks (CMJ and running gait) thus, it is not essential to predict injury risk based on asymmetry difference found within one attribute only. Thereby, a multi-attribute (Figure 1.4) levels of assessment for bilateral asymmetry which consist of a mixture of both unilateral and bilateral tests is believed to offer for researchers and practitioners a more holistic and solid assessment tool for bilateral asymmetry in lower limbs and could dramatically enhance athletes' performance by screening them to diagnosing bilateral asymmetry or following-up their asymmetry development throughout the season. These screenings could be utilised as a tool for predicting risk of injury or on the other hand, may enhance their performance in certain skills.

The methodology used in the last study (Chapter 7) could also provide a useful insight to practitioners in how to conduct low-cost studies at professional set-ups as this study has conducted utilising a treadmill, a pair of force plate platforms and few slow-motion cameras rather than using time-consuming equipment such as the three-dimensional gait analysis system or operating expensive systems like the isokinetic dynamometers in order to extract the same parameters. Finally, this study can be implemented as a benchmark for other studies related to bilateral asymmetry as it has provided norms based on large sample size of healthy athletes whereas several studies have displayed by far smaller recruited populations. Therefore, it can lessen the time consumed for the future studies as it eliminates the need to recruit healthy subjects when conducting comparative studies about bilateral asymmetry in lower limbs.

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11.0 APPENDICES

APPENDIX A: Ethical Approval Form

University of Salford MANCHESTER

Rachel Shuttleworth
College Support Officer (R&I)
Research, Innovation and Academic
Engagement Ethical Approval Panel
College of Health & Social Care

29 June 2012

Dear Ahmed,

RE: ETHICS APPLICATION HSCR12/07

– An investigation into the relationship between strength imbalance, flexibility and leg length discrepancies on left and right leg asymmetry.

Following your responses to the Panel's queries, based on the information you provided, I am pleased to inform you that application HSCR12/07 has now been approved.

If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible.

Yours sincerely,

Rachel Shuttleworth

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APPENDIX B1: Consent Form

University of Salford MANCHESTER

An Investigation into the relationship between anthropometric, anatomical, neuromuscular and structural lower limb bilateral asymmetry in athletes.

Subject Identification Number:

RGEC Ref No:

Name of Researcher: *Ahmed Aldukhail*

Tick for Yes

1. I confirm that I have read and understood the **Patient Information Sheet** for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐
3. **I agree to take part in the above study.** ☐

------------------------------------	------------------	--------------------------
Name of Participant	Date	Signature
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Name of Person Taking Consent	Date	Signature
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Name of Researcher	Date	Signature

1 copy to be given to participant; 1 copy to be kept by researcher

APPENDIX B2: Consent Form

Parents' Consent Form –
Medical Assessments and Performance Tests

1. General Consent

The Sports Curriculum at Aspire Academy is designed to safely maximize the health and fitness status of your child, in order to prepare them to train and compete at their best level.

As part of the Aspire Academy curriculum your child will be required to partake in a number of routine medical assessments and sports science performance tests across the year.

These medical assessments and performance tests are important as they provide information about the health, growth and development, and fitness level of your child. This information will allow the Aspire Academy to monitor developmental progress and safely build the training program needed to safely enhance sports performance.

The data collected in these routine assessments will provide useful information for our athletes, coaches, medical staff and sports scientists.

Aspire Health Centre (under the auspice of the National Sports Medicine Program and Aspetar Hospital) is committed to providing the necessary health care service along with comprehensive medical screening for your son. This important service allows us to understand the health status of your child. This knowledge promotes the safe and effective management of a program of physical conditioning necessary to enhance your son's sporting performance.

In the event that an injury occurs, most of the necessary diagnostic procedures, treatment and rehabilitation can be provided in the Aspire Health Centre and at Aspetar Hospital.

2. Medical Consent

Procedure to be followed

The following medical clearance assessment will be undertaken at the start of each academic year:

- A nurse administered health questionnaire will be conducted with recording of vital signs and results of laboratory tests (blood, urine and saliva)

- A lung function assessment, dental assessment, musculoskeletal assessment, cardiac screening tests (ECG & Echocardiography) and assessment of body composition and skeletal health and biological development (using wrist XRAY and DEXA) will be conducted

- A sports Medicine Physician will review the test results and perform a physical examination and recommend any required follow up

This examination and medical screening will occur once per year at the commencement of the new school year.

All medical tests performed are standardized and have the normal risks associated with undergoing such medical assessments. The use of ionizing radiation (X-Ray) once per year and the use of the DEXA (a low energy X-Ray) for the assessment of bone health are within acceptable limits as set by the appropriate standards generating organizations.

3. Sports Science Consent

The Football Performance Science and Sports Science Department at Aspire Academy work closely with the coaching staff to ensure that athletic training programs are constructed correctly. These Departments conduct a number of routine assessments as part of the annual curriculum. These assessments allow Aspire Academy staff to scientifically monitor the fitness status of your son and precisely measure how training enhances performance.

Procedures to be followed:

Routine tests will include:

- Measurement of endurance capacity. These assessments will measure the stamina of your son. Stamina is a key component of sporting success and is usually measured by running or cycling to voluntary exhaustion. A number of respiratory tests are conducted to measure key variables in endurance performance.

- Measurement of Speed and Acceleration. This key component of performance is measured by performing sprint type tests on a track.

- Measurement of a power and muscle strength. These variables are measured using tests that include jumping or muscle performance tests.

 Measurement of patterns of growth and development. These variables are assessed using changes in height and weight, skinfold thickness and bone health. Low energy X-Ray (DEXA) is used to accurately quantify bone density. Blood and saliva samples are routinely taken to measure bone health (Vitamin D) and maturational status (Testosterone).

 Measurement of running gait and technique analysis. Key performance data will be collected by high speed filming and other associated technologies to allow athlete to view their technique and modify technique were required.

 Measurement of mental concentration, attention and psychological stress. Concentration and focus of attention are key performance variables. These can be easily measured using psychological tests. In addition, athletes will be taught how to reduce anxiety in order to improve performance. An increase in performance can be measured by changes in psychophysiological variables.

 Measurement of mental training. Our sports psychologists will teach athletes how to set performance goals and how best to psychologically prepare for training and performance. This will involve individual and group work with our Sports Psychologists.

The benefit of these Sports Science assessments is that the performance plans for each athlete can be specifically tailored to suit the individual. Each individual will have access to their own fitness data as they progress to the academy.

The risks performing theses routine tests are very low and considered to be acceptable for the age and physical maturity of the participants.

All data will be anonymized and stored for up to 10 years. This data may be analyzed for education, research training and scientific purposes.

4. Confidential Information

All medical information will be stored in a manner consistent with the preservation of confidentiality and privacy.

Any information used for research purposes will be collected using techniques to ensure that all information is anonymous and stored electronically for a minimum of 10 years during which time it may be analyzed for educational, research and scientific purposes. The benefits of this data collection are that it allows for the accurate assessment of the health status of your child. It also provides information on the growth pattern of your child.

5. CONSENT

I, the undersigned, parent of the student-athlete:

Name: --

Grade:---------------------------

Sport: ---------------------------------------

agree that Aspire Academy and Aspetar may use and permit other person to use information for the purposes of education and research that:

a) Contained in medical reports and anonymised clinical and performance data (including pictures for promotional material)

b) Collected in the course of routine tests for educational, treatments, research and scientific purposes,

I, the undersigned agree that Aspire Health Centre and Aspetar Hospital have permission to provide primary health care interventions to diagnose, treat and rehabilitate my child in the advent of injury or illness, as per the Aspetar general consent.

I, the undersigned, have entered into this agreement in order to support the development of scientific knowledge of treatment of injury and performance enhancement.

The undersigned can withdraw consent to the use of clinical data for research and educational purposes without impacting their progress through the academy.

Parent's name:--- Signature:---------------------------

Date: --------------/-----------/-------------------

Parent's Copy

File's Copy SS-F-02 rev.0 issued 28/07/2013 Page 4 of 4

APPENDIX C: Subject Information Sheet

An investigation into the relationship between strength imbalance, flexibility and anthropometric discrepancy, on right and left legs asymmetry in sport-specific groups of athletes.

School of Health, Sports and Rehabilitation Sciences

Participant Information Sheet

Title of Project: An investigation into the relationship between strength imbalance, flexibility and anthropometric discrepancy, on right and left legs asymmetry in sport-specific groups of athletes**.**

Information about this document

You are being invited to take part in a research study to help us understand more about the influence of lower extremity muscle asymmetry imbalances in team sport athletes. Before you decide, it is important for you to understand why the research is being done and what it will involve. This document gives you important information about the purpose, risks, and benefits of participating in the study. Please take time to read the following information carefully. If you have any questions then feel free to contact the researcher whose details are given at the end of the document. Take time to decide whether or not you wish to take part.

Background to the study

The aim of the study is to investigate the presence of muscle imbalances in professional team sport athletes and evaluate the underlying causes. The studies objectives are to therefore: first, to identify whether team sport athletes have lower limb strength & power asymmetry measured by force platform and isokinetic dynamometry methods; and second, to investigate and identify underlying factors responsible for lower limb imbalances (i.e. age, injury, anatomical, etc.); as well as to evaluate whether functional field based tests can identify imbalances in athletes.

The study will involve 60 team sport athletes. Participating in this study is completely voluntary and you may withdraw at any time.

What will happen to me if I participate in this study?

If you agree to take part in the study, you will be required to participate in field based tests at your training centre or ground. You shall also be invited to visit the movement science laboratory at Salford University on one occasion.

Testing at the movement science laboratory at Salford University will involve:

- Taking consent and completing a health questionnaire.
- Explanation and performance of the following testing procedures.

1. **<u>Isokinetic strength testing: Hamstrings/Quadriceps (concentric) at 60°/s</u>**

An isokinetic device (Kin Com dynamometer, Chattanooga Group, USA) will be used to measure the peak force of both hamstring and quadriceps muscles in both limbs, measurement will be taking for both lower limbs in both modes concentric and eccentric at speed of 60 degrees per seconds. The device is reliable for test re-test to measure peak forces (Feiring et al., 1990).

2. **<u>Countermovement Jump Test on Dual Force Plates</u>**

Two Kistler in-ground force plates will be used to measure the ground reaction force independently from each foot. This will be with your body weight firstly, then with an extra 20% of your body weight and then with 40% of your body weight. You shall then do a single-legged jump on each leg on the force plates.

3. **<u>Hip ROM</u>**

The Modified Thomas Test (Harvey, 1998) will be performed to record the hip range of motion and to assess the flexibilities of iliopsoas, quadriceps and tensor facia lata/iliotibial band.

4. **<u>Knee ROM</u>**

The Active Knee Extension Test (Gajdosik & Lusin, 1983) will be performed to record the knee range of motion. It is specifically designed to exclude any neurological or physical factors that might occur when stretching the hamstring muscle group.

5. **<u>Ankle ROM</u>**

Ankle ROM will be performed with a Universal Goniometer to record the range of motion of the ankle's dorsiflexion.

6. **<u>Leg Length discrepancy (LLD)</u>**

Your leg length will be measured with a tape measure whilst you are lying down on a plinth.

7. **Thigh and calf circumference measurements**

Your thigh and calf circumference will be measured with a tape measure.

8. **Functional Tests**

- One-legged Hop test (Noyes et al., 1991). This test consists of jumping as far as you can from one leg and landing on the same leg.
- Three-Hop test (Noyes et al., 1991). This test consists of 3 consecutive hops on the same leg for as far as possible and the total distance will be measured.

RISKS & POTENTIAL BENEFITS OF THE STUDY

What risks are involved in participating in the study?

This is a very simple, straight forward study with negligible risks. As with all types of exercise there are potential risks of injury. To ensure that this is minimised you will undergo a thorough warm up and have a familiarisation session. You may experience some muscle soreness with eccentric exercise but this normally subsides after a few days.

Will my taking part in the study be kept confidential?

All information which is collected about you during the course of the research will be kept strictly confidential; data will be collected and stored anonymously on a password protected computer. All data will be stored in line with the University of Salford's guidelines to ensure no breach of data protection. Only the researcher and the supervisor will have access to your information. Data will be disposed of securely after 3 years

What benefits are involved in participating in the study?

Taking part in this particular study will enable you to discover whether you have a muscle imbalance in one of your legs. This could help answer certain questions as to why you favour one limb to the other. The underlying causes may not be certain but we can test to see if anthropometric issues contribute to the strength imbalance.

ENDING THE STUDY

What if I want to leave the study early?

You can withdraw from the study at any time. If you wish to withdraw from the study, all information and data collected will be removed from the computer which stores your information and will not be used for further investigation. Should you withdraw you will not be disadvantaged in anyway.

CONFIDENTIALITY OF SUBJECT RECORDS

Will my taking part in this study be kept confidential?

All information which is collected about you during the course of the research will be kept strictly confidential. Any information about you which leaves the University of Salford will have your name and address and any other identifying features removed so that you cannot be recognized from it.

What will happen to the results of the research study?

The researcher will give you feedback on your test performance should you wish to receive it. There is a strong possibility that this work may be presented at a conference or published in a journal. Should this happen your results be published anonymously.

CONTACT INFORMATION

If you require more information about the study, want to participate, or if you are already participating and want to withdraw, please contact

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Record of Information Provided

Your will receive a copy of the information sheet and a signed consent form to keep for your personal records.

Thank you very much for taking time to read this document

We appreciate your interest in this study and hope to welcome you at the School of Health, Sport and Rehabilitation Sciences, University of Salford

APPENDIX D: Data Collection Form

NAME____

DATE____

M_________ F__________

AGE___________________

HEIGHT (cm)________________

WEIGHT (kg)________________

SPORT_____________________

PREVIOUS INJURIES_________________________________

FLEXIBILITY (degree)

Hamstrings

	RIGHT	LEFT
1		
2		
3		
4		
MEAN		

Quadriceps

	RIGHT	LEFT
1		
2		
3		
4		
MEAN		

1LH

	RIGHT	LEFT
1		
2		
3		
4		

1LTH

	RIGHT	LEFT
1		
2		
3		
4		

ISOKINETIC STRENGTH

	RIGHT		LEFT	
	Extensors	Flexors	Extensors	Flexors
Concentric peak torque 60°/s				

COUNTERMOVEMENT JUMP

	1	2	3
CMJ BW			
CMJ BW+20%			
CMJ BW+40%			
1LCMJ RIGHT			
1LCMJ LEFT			

Running gait reporting:

	Right Foot			Left Foot		
Step / Contact	Contact time (s)	Flight time (s)	Swing time (s)	Contact time (s)	Flight time (s)	Swing time (s)
1						
2						
3						
4						
5						
Average						
SD						

Given that the time to complete one **step** is the sum of the contact and the flight time, we can calculate:

Average Time to complete one step (Right to Left) = ___________seconds

Average Time to complete one step (Left to Right) = ___________seconds

Step Frequency (Right to Left) ___________ Hz

Step Frequency (Left to Right) ___________ Hz

Knowing that the treadmill belt speed was 12 km/h, we can determine the average stride lengths (Right to Left and Left to Right).

Stride Length (Right to Left) ___________ m

Stride Length (Left to Right) ___________ m

	Contact Time (s)	Flight Time (s)	Swing Time (s)	Step Time (s)	Step Frequency (Hz)	Stride Length (m)
Asymmetry (L/R) %						

APPENDIX E: Published Poster at ESB-Aug-2013

CLINICAL DIAGNOSIS OF STRENGTH AND POWER ASYMMETRY

Ahmed Aldukhail, Paul Jones, Hannah Gillard, Philip Graham-Smith
Directorate of Sport, Exercise & Physiotherapy, University of Salford, Manchester, UK
Email: a.m.aldukhail@edu.salford.ac.uk

INTRODUCTION

Bilateral asymmetry (BA) is a term frequently used in the fields of sports performance and rehabilitation, describing substantial deviation from normative data or muscle performance differences between limbs [Schlumberger *et al*, 2006].

Strength imbalances are examined using a variety of testing methods and modes. Surprisingly, there is no definitive criterion for the clinical diagnosis of asymmetry. Moreover, there are several issues with respect to how a 'normal' difference between limbs is determined. Studies that have compared left (Lt) and right (Rt) limbs tend to find close to zero differences in mean strength/power and rely on measures of variance between subjects as the criterion [Newton *et al*, 2006]. These do not provide a relevant measure of a 'typical' difference.

Within closed chain (CC) bilateral (Bi) tests, average (Avg.) forces over the entire force production phase are likely to mask differences in eccentric (ECC) and concentric (CON) phases and these have not been investigated.

AIM

To establish true values for typical levels of asymmetry in open chain (OC) and CC, unilateral and Bi tests and introduce the term 'absolute asymmetry value' (AAV).

Figure 1: 1LTHJ test

METHODS

Sixty three injury-free athletes (57 males, 6 females, mean±SD: age 22.5±4.2 years, height 180±9 cm and mass 83±17.5kg) underwent a battery of tests as follows:

OC: Isokinetic strength testing (Kin Com dynamometer) of the quads (Q) and hamstrings (H) muscle groups in CON mode at $60^{\circ}\cdot s^{-1}$ were determined.

CC (Bi): Peak forces within the movement phase and Avg forces in ECC, CON and overall movement of 3 CMJ were determined.

CC Unilateral (Uni): Uni CMJ (Peak and Avg force), 1-legged hop jump (1LHJ) and 1-legged triple hop jump (1LTHJ) for distance were measured

Asymmetry was calculated using the formula:

Abs [(Lt leg – Rt Leg) / (Max of Lt or Rt leg)] x 100.

RESULTS AND DISCUSSION

The data presented in Table 1 can be considered as typical asymmetry scores for a range of OC and CC tests of Arbitrary values of 10-15% [Impellizzeri *et al*, 2007] can be considered too conservative and do not reflect the mode of test utilised. The 'typical' level of BA varies between different testing modalities ranging from 10.3% (H CON) to 0.8% (Avg. whole of Bi CMJ). It is important also to determine asymmetry in ECC and CON phases as the Avg force over the entire movement phase may balance differences out.

Table 1: Mean ± SD and AA % for the OC & CC measurements of both the Rt and Lt legs (n=63).

TEST	Rt Mean ± SD	Lt Mean ±SD	Avg. Asymmetry Mean ±SD (%)	AAV Mean ±SD (%)
OC				
Q CON	224.7 ± 42.5	227.4 ± 38.2	-1.8 ±9.37	8.29 ±6.43
H CON	118.6 ± 22.6	109.8 ± 17	-3.1 ±9.87	10.28 ±5.96
CC Bi test				
Peak	927.7 ±198.3	965.3 ±197.2	-5.0 ±13.7	8.37 ±11.95
Avg. (whole)	819.5 ±170.5	822.5 ±170.6	-0.4 ±1.9	0.79 ±1.82
Avg. ECC	424.4 ± 89.7	427.0 ±129.5	-2.1 ±32.4	8.47 ±6.54
Avg. CON	774.5 ±160.6	758.1 ±169.5	1.8 ±11.5	6.49 ±5.06
CC Uni test				
Peak	1538 ± 297	1545 ±319	-0.5 ±7.1	5.10 ±4.88
Avg. (whole)	913.4 ±206.8	917.7 ±222.1	-0.4 ±5.6	2.69 ±4.95
1LHJ	169.4 ±32.73	168.1 ±32.74	0.26±11.6	7.63 ±8.68
1LTHJ	558.3 ±81.22	563.8 ±89.74	-0.98 ±7.6	5.06 ±5.67

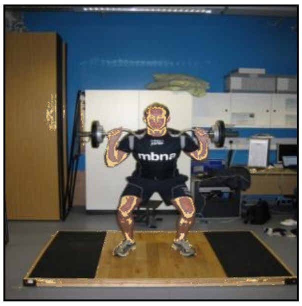

Figure 2: Bi CMJ test

Figure 3: Isokinetic strength test

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APPENDIX F: Published Poster at ECSS-Jul-2014

Comparison of Asymmetry in Bilateral and Unilateral Movements

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Introduction

Bilateral asymmetry is a term used to describe deviations in functional performance between left and right limbs. The underlying premise is that substantial deviations create compensatory movements, modify loading patterns and may lead to injury. Whilst the theory seems plausible, limited evidence exists to substantiate the argument. Before any association with injury is established clear criteria and thresholds need to be set in order to clinically diagnose an asymmetry, and these thresholds will be specific to the parameter of interest. Clinicians have generally adopted arbitrary values of around 10% to 15% but with no clear rationale or appreciation of typical differences between limbs.

In addition to this the current trend to test 'functional' movements have raised the question as to whether findings from bilateral and unilateral tests show agreement.

Objectives

The purpose of this study was to:

- quantify the typical differences between limbs for selected parameters of interest and set thresholds above which an asymmetry can be classified.
- examine the level of 'agreement' between diagnoses of asymmetry for a bilateral CMJ and a functional unilateral movement (running).

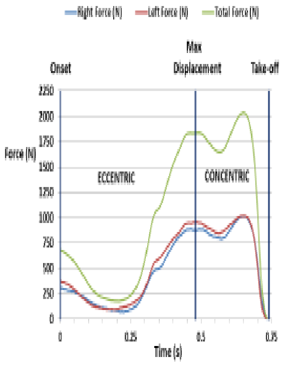
Methods

144 athletes aged between 12 and 18 underwent screening which included assessments of running and jumping.

Three maximal CMJ's were performed on two Kistler 9286AA portable force platforms sampling at 1000Hz. Left and right leg forces were summed to establish total force and the point of maximal displacement was used to define the transition between eccentric (Ecc) and concentric (Con) phases (Fig 1).

Average forces in the Ecc and Con phases and the peak forces were extracted. Asymmetry was expressed as the absolute difference between limbs % contribution to the total force.

Fig 1. Vertical force graph for the CMJ



Athletes ran on a Woodway treadmill at 12km/h for 30s whilst been recorded by six synchronised Quintic high speed video cameras (125fps). Mean contact time, swing time and step length over 6 strides for each limb were calculated.

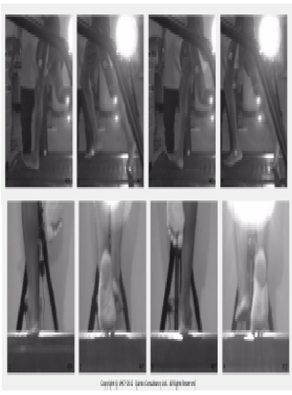


Fig 2. Instants of Contact and Toe-off to determine contact time, swing time and step length

Asymmetry was determined as the absolute % difference between left and right values divided by the mean of left and right.

Asymmetry thresholds for each parameter were determined as the mean absolute difference plus one SD of all athletes.

In order to examine the agreement in diagnoses of asymmetry one or more of the 3 variables in each movement had to exceed the asymmetry threshold.

Results & Discussion

The asymmetry thresholds and the frequency in which these were exceeded can be seen in Table 1.

CMJ	Peak Force	Ave Ecc. Force	Ave Con. Force
Threshold	7.6% (11)	11.7% (37)	7.3% (12)
Running	Contact Time	Swing Time	Step Length
Threshold	9.1% (16)	5.3% (19)	8.9% (16)

Table 1. Asymmetry thresholds and (frequency) for each parameter

Using our criteria 44.4% of the athletes exhibited an asymmetry in either running or jumping (Table 2).

The most frequent asymmetry was in the eccentric phase of the CMJ suggesting poor movement control in bilateral movement.

The agreement in diagnosis between the CMJ and running was 18.8% suggesting that asymmetries should be assessed in both unilateral and bilateral movements.

	CMJ only	Running only	CMJ & Running
Asymmetries	30 (20.8%)	22 (15.3%)	12 (8.3%)
Total Asymmetries		64 / 144	44.4%
Agreement (with asymmetry)		12/64	18.8%
Agreement (no asymmetry)		80/144	55.6%

Table 2. Summary of Asymmetries

Conclusion

1. Criteria has been established to diagnose asymmetry.
2. 44.4% of the athletes had at least 1 parameter above the threshold.
3. A low agreement of 18.8% suggests that asymmetry should be assessed in both unilateral and bilateral movements.
4. The association between diagnosis of asymmetry ('risk') with actual injury occurrence needs further investigation.

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APPENDIX G: Published Poster at ISBS-Jun-2015

AGREEMENT BETWEEN ATTRIBUTES ASSOCIATED WITH BILATERAL JUMP ASYMMETRY

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INTRODUCTION

- The underlying premise of assessing lower extremity asymmetry is to evaluate the possible compensatory effects on movement and examine how asymmetrical differences may relate to performance and injury risk.
- Many sports skills require athletes to frequently repeat the execution of unilateral and asymmetrical movements and consequently this may initially lead to an enhancement in performance.
- Prolonged exposure to these movements may lead to asymmetrical differences in strength, power and joint ranges of motion due to the unique loading patterns and coordination of movement, potentially manifesting themselves in bilateral training exercises and create compensatory effects.

LIMITATIONS OF PAST RESEARCH

- The association between asymmetry and injury risk remains theoretical.
- Whilst some studies have examined relationships between strength and jump asymmetry (Impellizzeri et al. 2007; Newton et al. 2006), there has been no holistic examination of additional factors that may be associated with it, e.g. anthropometrical differences, ranges of motion or single leg jumping performance.
- Classifications of 'left-right' or 'dominant - non dominant' are not always helpful in establishing a true typical difference between limbs (as means are close to zero)
- Arbitrary thresholds of 10% (Schiltz et al., 2009) to 15% (Bennell et al., 1998; Croisier et al., 2002) have been proposed, but these would be inappropriate for measures such as leg length discrepancy where differences of 10% are extremely unlikely.

PRACTICAL RELEVANCE

- In clinical scenarios it is more meaningful to classify whether an athlete is asymmetrical or not in order to prescribe an intervention.
- Every measure would need a specific threshold, above which an asymmetry could be classified.
- To understand the real association it would be of more interest to examine the level of agreement between the diagnoses of asymmetry between attributes.

AIMS

- The aims of this study were to establish thresholds for the diagnosis of lower extremity asymmetry and to determine the level of agreement in the diagnoses of asymmetries between bCMJ with strength, anthropometry, flexibility and single leg jump attributes.

METHODS

- 145 subjects from a diverse range of sports (124 male, 21 female), average age of 22 ±5 years participated in the study.
- 73 subjects were professional athletes and 72 were recreational.
- Screening battery involved assessments of asymmetry in bCMJ, strength, anthropometrical measures, lower extremity flexibility and single leg jump tests. Three criteria were used for each attribute (see tables below).
- bCMJ asymmetry expressed as the difference in the percentage contribution to the total force:

$$bCMJ\ Asymmetry\ \% = \left[\frac{Abs[Force\ Leg\ A - Force\ Leg\ B]}{[Force\ Leg\ A + Force\ Leg\ B]}\right] \times 100$$

- For all other tests asymmetry was determined using the formula:

$$Asymmetry\ \% = \left[\frac{Abs\ [difference\ between\ Limbs]}{[Max\ of\ Limbs]}\right] \times 100$$

- Asymmetry thresholds were diagnosed based on exceeding the Mean ± SD of the absolute difference between limbs.
- For an attribute to be diagnosed as 'asymmetrical' at least one criteria had to exceed its threshold.
- Countermovement jump

BILATERAL CMJ	PEAK FORCE	AVE. ECCENTRIC FORCE	AVE. CONCENTRIC FORCE
TEST 	2 Kistler force platforms type 9286A AA, 1000Hz		
THRESHOLD (%)	10.1	14.4	11.6
NO. OF ATHLETES EXHIBITING AT LEAST ONE ASYMMETRIES	40 / 145 (27.6%)		

- Flexibility

FLEXIBILITY	QUADRICEPS	HAMSTRINGS	GASTROCNEMIUS
TEST			
THRESHOLD (%)	10.6	27.5	13.7
NO. OF ATHLETES EXHIBITING AT LEAST ONE ASYMMETRY	57 / 145 (39.3%)		

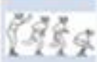
- Anthropometry

ANTHROPOMETRY	LEG LENGTH	THIGH CIRCUMFERENCE	CALF CIRCUMFERENCE
TEST			
THRESHOLD (%)	1.0	3.8	3.2
NO. OF ATHLETES EXHIBITING AT LEAST ONE ASYMMETRY	46 / 145 (31.7%)		

- Strength

STRENGTH	QUADRICEPS	HAMSTRINGS	H / Q Ratio
TEST 	BIODEX SYSTEM 4 CONCENTRIC PEAK TORQUE (GRAVITY CORRECTED) 60 deg/s		
THRESHOLD (%)	17.6	21.4	20.4
NO. OF ATHLETES EXHIBITING AT LEAST ONE ASYMMETRY	30 / 145 (20.7%)		

- Single Leg Jump Performance

SINGLE LEG JUMPS	VERTICAL JUMP	HOP FOR DISTANCE	TRIPLE HOP FOR DISTANCE
TEST			
THRESHOLD (%)	18.8	13.9	11.3
NO. OF ATHLETES EXHIBITING AT LEAST ONE ASYMMETRY	29 / 145 (20.0%)		

- Agreement in the diagnoses of asymmetry were calculated as follows:

$$Overall\ Agreement\ (\%) = \left[\frac{No.of\ like\ for\ like\ diagnoses}{No.of\ Subjects}\right] \times 100$$

$$Asymmetry\ Agreement\ (\%) = \left[\frac{No.of\ like\ for\ like\ diagnoses\ of\ Asymmetry}{No.of\ bCMJ\ Asymmetries}\right] \times 100$$

RESULTS & DISCUSSION

- Asymmetry thresholds can be seen to be as low as 1% for leg length discrepancy to 27.5% for hamstring range of motion.
- Using these thresholds a total of 40 asymmetries were detected in bCMJ, 57 in flexibility, 46 anthropometry, 30 strength and 29 in single leg jumps.
- The levels of agreement in diagnosis of asymmetry between bCMJ and the other attributes are presented below:

AGREEMENT IN DIAGNOSES	OVERALL	ASYMMETRIES ONLY
FLEXIBILITY	72 (49.7%)	12 (30.0%)
ANTHROPOMETRY	85 (58.6%)	13 (32.5%)
STRENGTH	97 (66.9%)	11 (27.5%)
SINGLE LEG JUMPS	102 (70.3%)	12 (32.5%)

- The overall level of agreement with bCMJ diagnosis highlighted levels of agreement between 49.7% for flexibility up to 70.3% for single leg jump performances.
- For the 40 bCMJ asymmetrical subjects each of the attributes were found to exhibit similar levels of agreement of between 27.5 to 32.5%.
- These relatively low levels of agreement highlight that bCMJ asymmetry is likely to be multi-factorial and not due to any one single attribute.
- The summation of asymmetries across all attributes led to a slight increase in agreement with bCMJ to 72.9%.
- The level of agreement between the summation of all attributes with actual bCMJ asymmetries was only 35.9%.
- We observed that 121/145 (83.4%) subjects carried at least one asymmetry across all attributes (including bCMJ) which was a far greater incidence of lower extremity asymmetry than first anticipated.

CONCLUSION:

- Definitive thresholds for individual criteria are required to classify whether an attribute is asymmetrical.
- We have successfully set thresholds for 15 criteria across 5 different attributes, including bCMJ, flexibility, anthropometry, strength and single leg jump performance.
- Associations based on the agreement in diagnosis of asymmetry was a novel approach and this provided a different insight into the relationship between attributes that may have an effect on the execution of a bCMJ.
- Results suggest that the majority of athletes carry at least one lower extremity asymmetry and they will be able to operate mostly injury free
- If asymmetry does have a cause-effect relationship to injury then the severity and combinations of asymmetries should be examined alongside other factors relating to the loading characteristics and mechanisms of specific injuries.

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International Society of Biomechanics in Sport, Poitiers, France, June 29th – July 3rd 2015.